

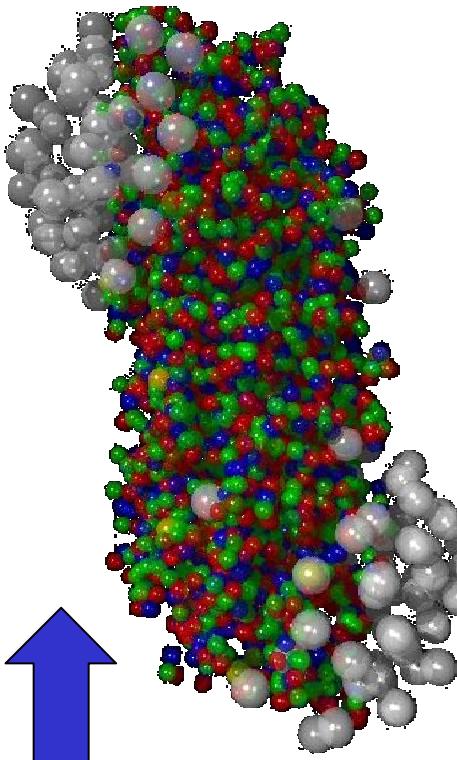
Insights From a New Generation of Proton-Nucleus Experiments @ AGS and SPS

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Columbia University

Outline

- Introduction & Motivation
- New generation of experiments
- Proton stopping/fragmentation
- Strange particle production
- Conclusions, comments

Why p-A now more than ever ?



- We want to understand

- Initial conditions

- Degrees of freedom

- QGP formed ??

- Assume we “understand” p-p

- Biggest difference between p-p & A-A:

- ⇒ Multiple scattering of nucleons ?

⇒ Which we do not understand in detail !!

⇒ Then how can we understand A-A ???

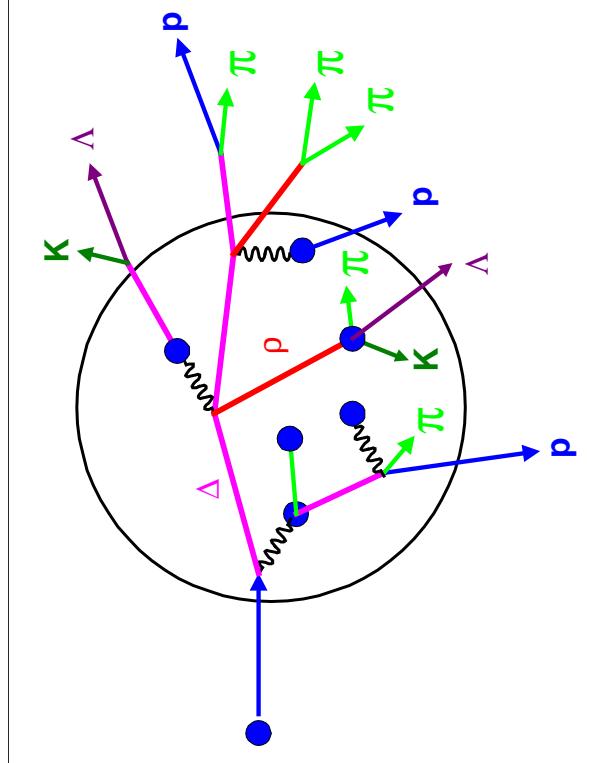
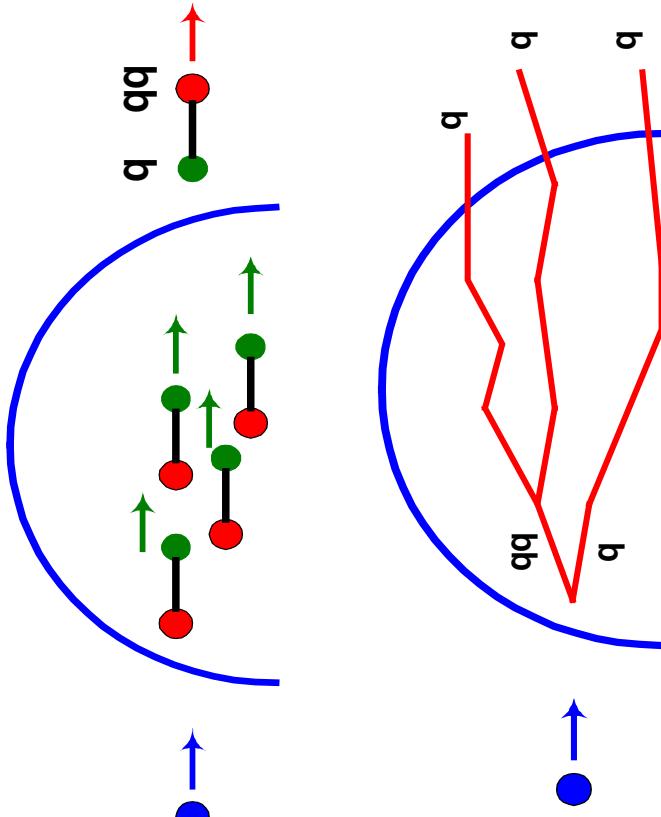
- How to study nucleon multiple scattering ?

⇒ proton-nucleus collisions

- Not enough to simply compare p-A & A-A data !!

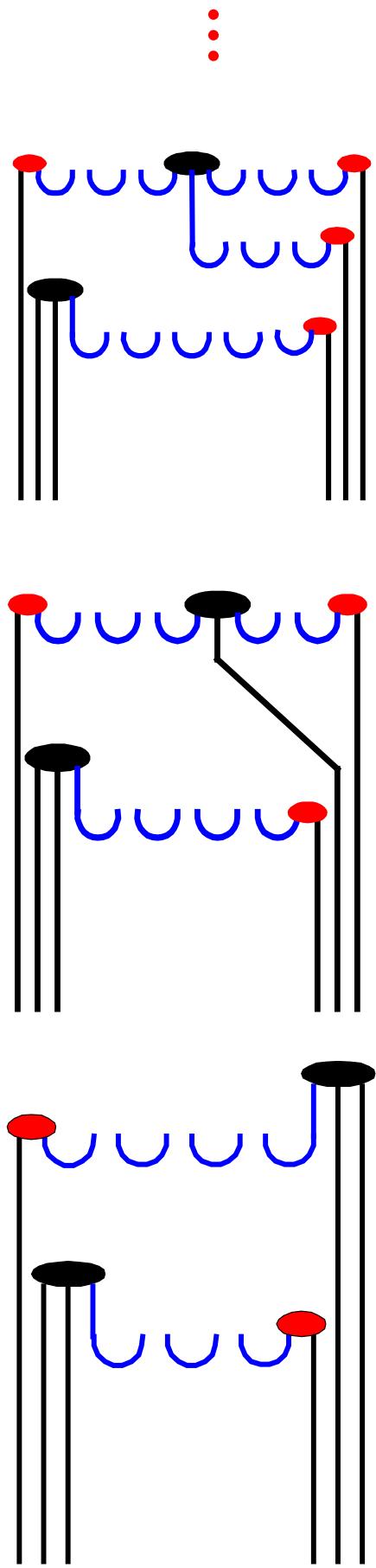
‘Pictures’ of p-A Dynamics

- Color dipole model
 - Excitation via qq – q string.
 - + string overlap (Ropes) ??
- Constituent quark model
 - Valence quarks relevant DOF.
 - Additive or not ?
- Resonance Model
 - Δ, N^*, ρ excitation, decay.
- **Critical issue: (talk focus)**
how does proton respond ?
 - Esp: in first few collisions
- **How does response affect final-state observables ?**



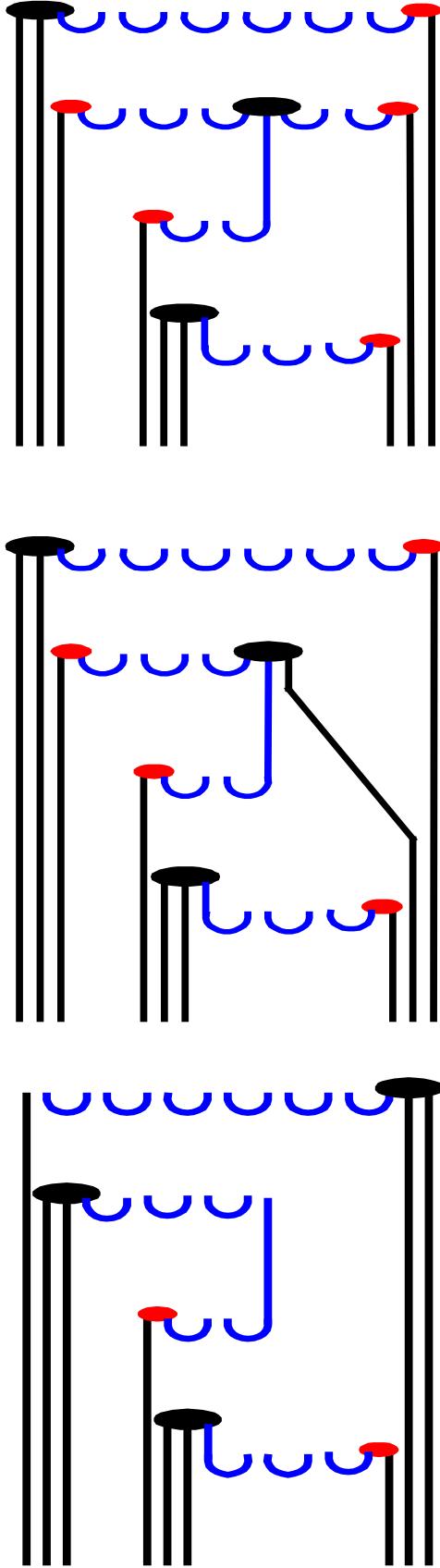
From p-p to p-A

- (more) rigorous model of p-p: “topological” expansion
- **Diquark splitting**
- **two-string Junction**



Increased “breakup” of proton

- Possible double scattering diagrams



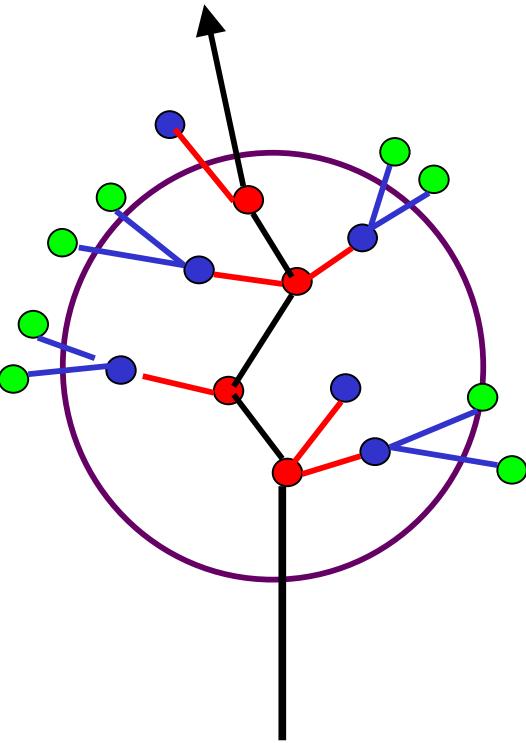
Proton more efficiently broken up?

p-A Collision Centrality

- Problem:

- Inclusive data insensitive to proton multiple scattering
- define $v = \#$ of “collisions”

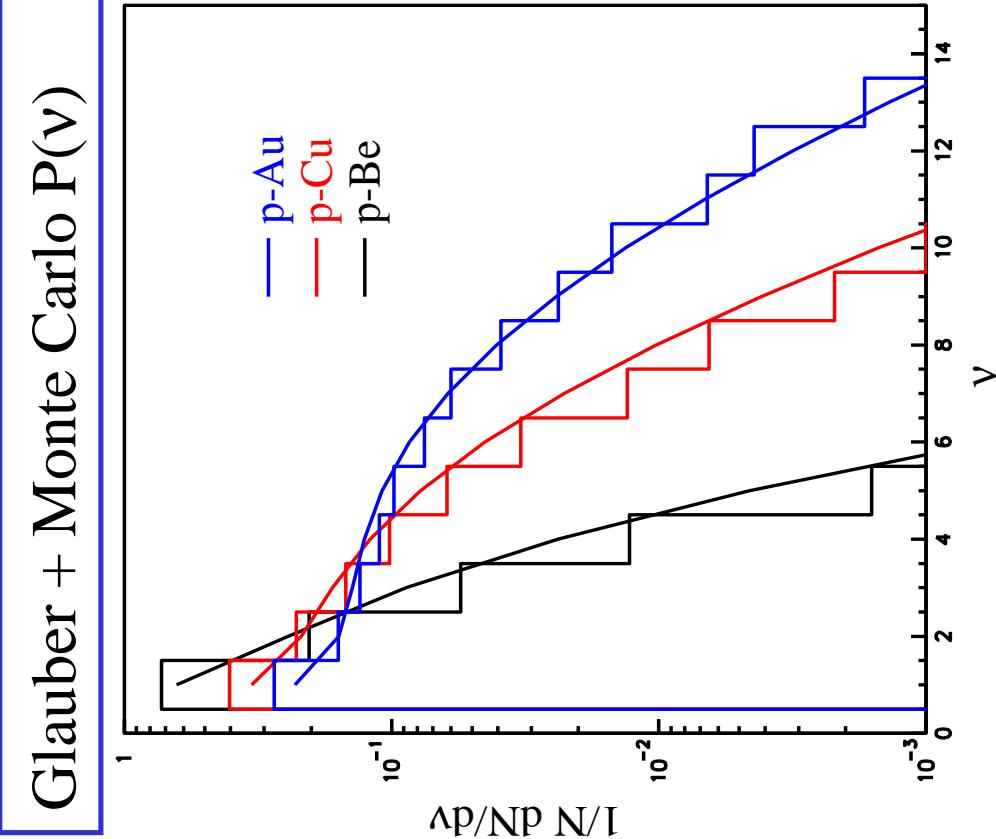
Glauber + Monte Carlo $P(v)$



Proton scatters $v = 4$ times

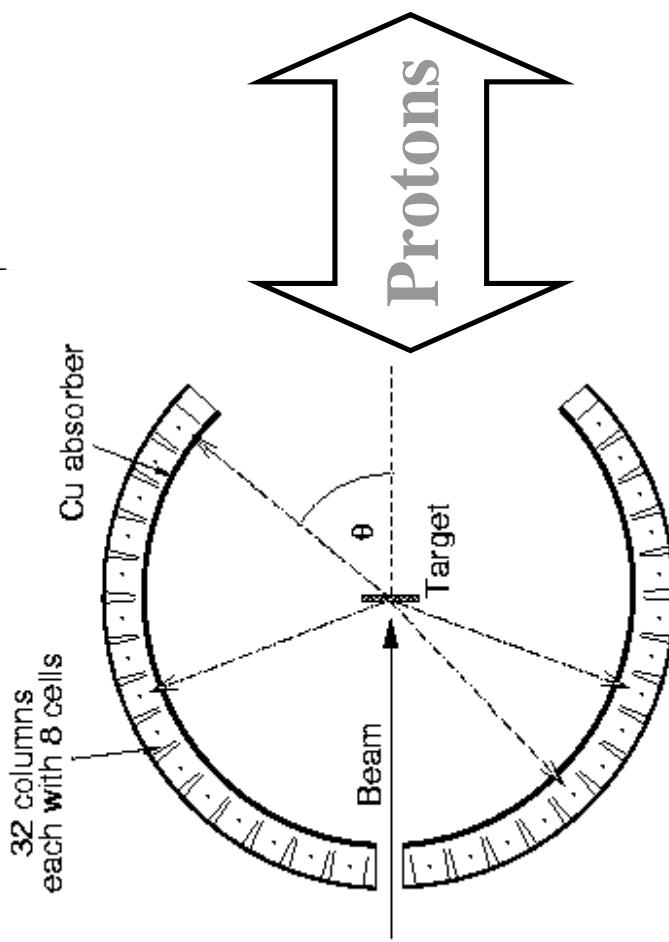
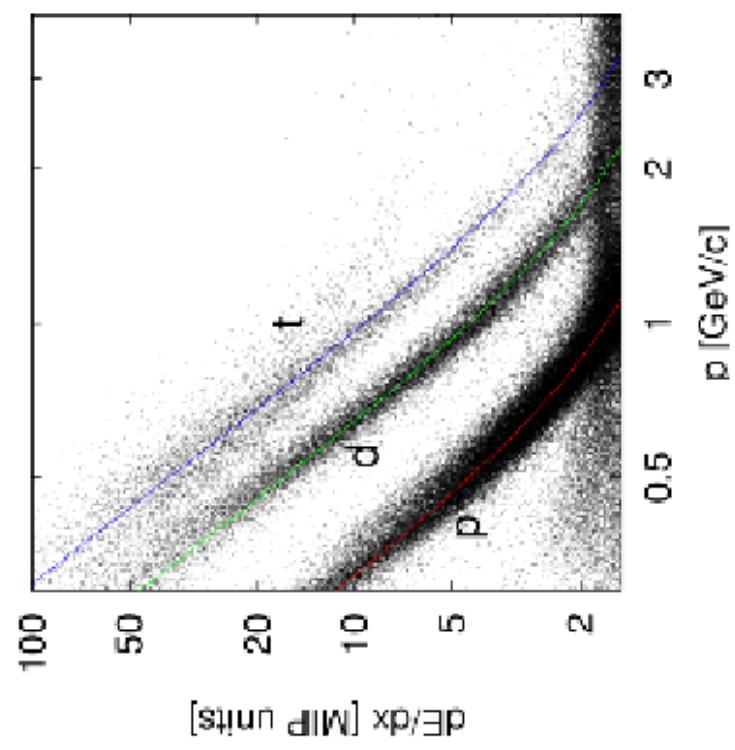
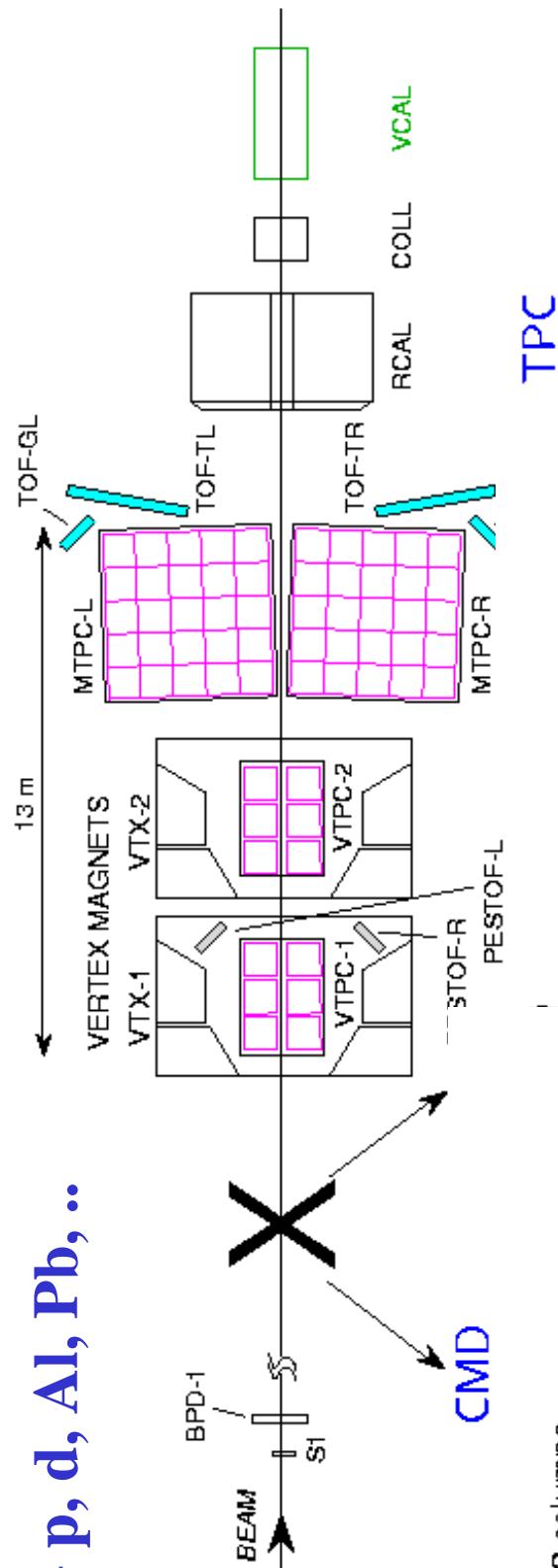
- Cascade **sensitive to v .**
- Measure # recoil (**grey**) protons **event by event**
- Statistically related to v
- Now practically possible with high statistics

- **E910, NA49**



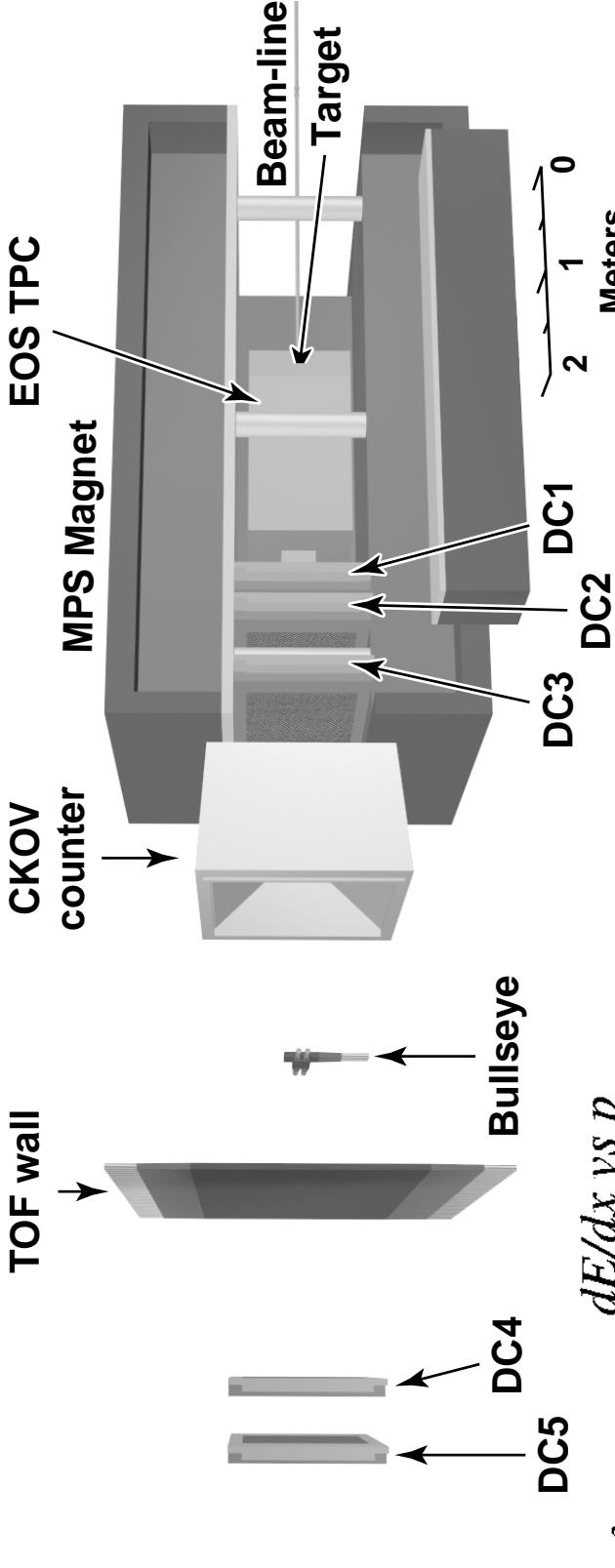
NA49 :: p-A

$\pi, p + p, d, Al, Pb, ..$

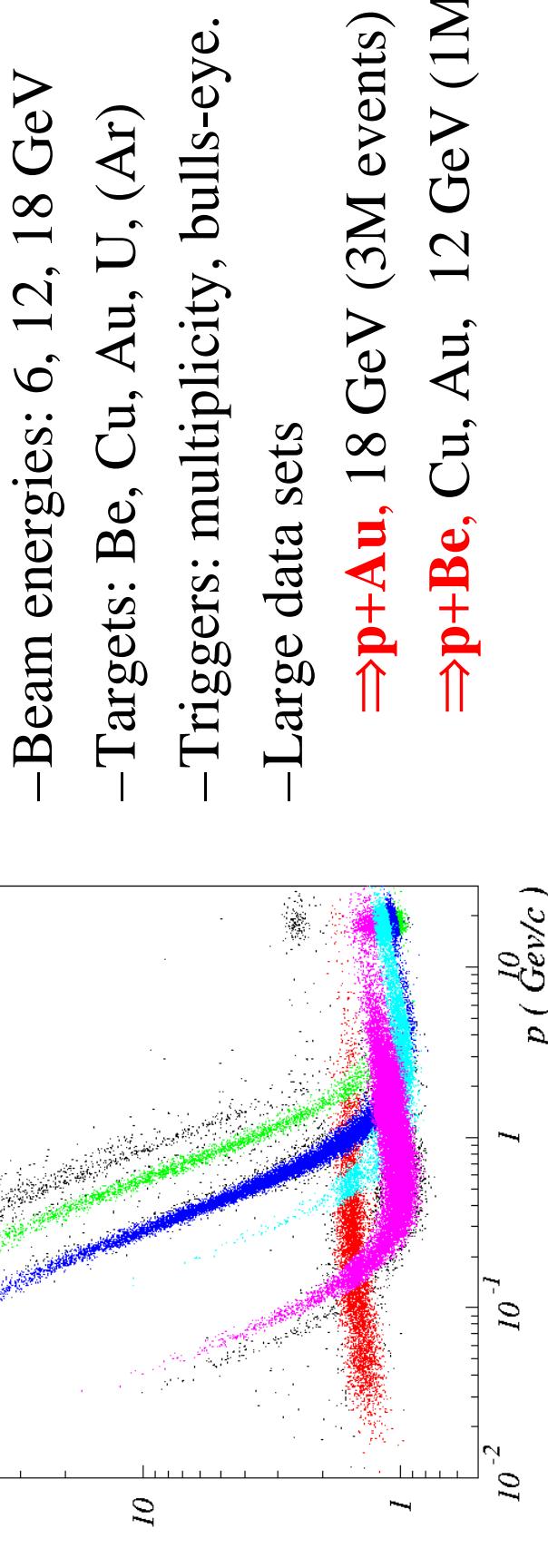


Cu absorber 200 μ eliminates black protons

E910 Spectrometer, dE/dx



E910 Data



- Beam energies: 6, 12, 18 GeV

- Targets: Be, Cu, Au, U, (Ar)

- Triggers: multiplicity, bulls-eye.

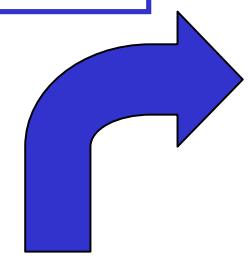
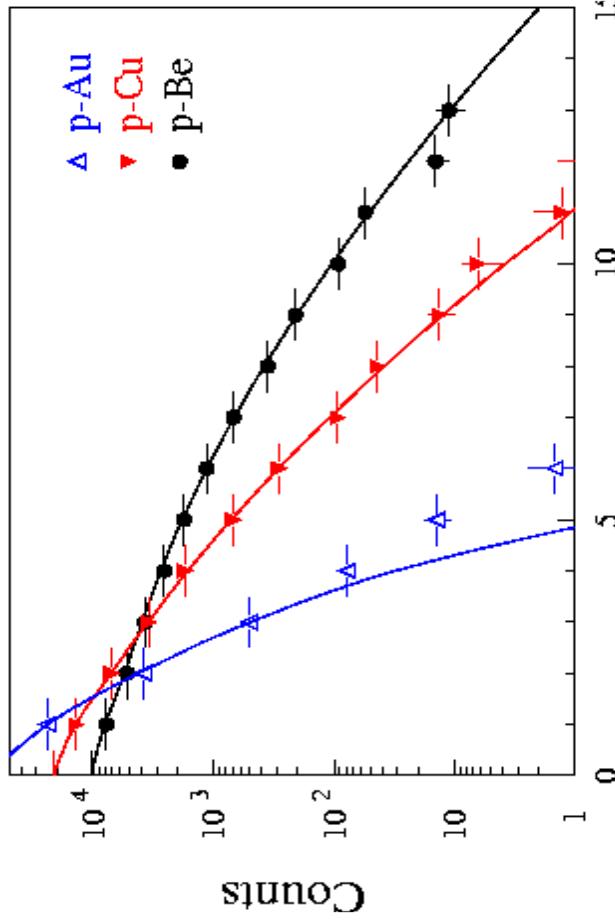
- Large data sets

$\Rightarrow \mathbf{p+Au}, 18 \text{ GeV}$ (3M events)

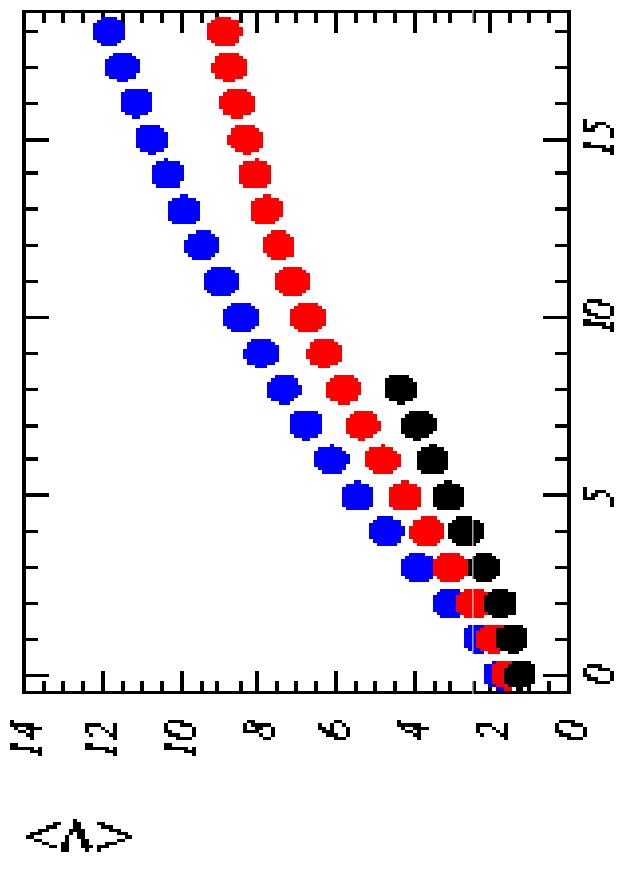
$\Rightarrow \mathbf{p+Be}, \text{Cu, Au}, 12 \text{ GeV}$ (1M).

E910 $N_{\text{grey}} \rightarrow \langle v(N_{\text{grey}}) \rangle$

E910 N_{grey} dist, Bulls-eye trigger



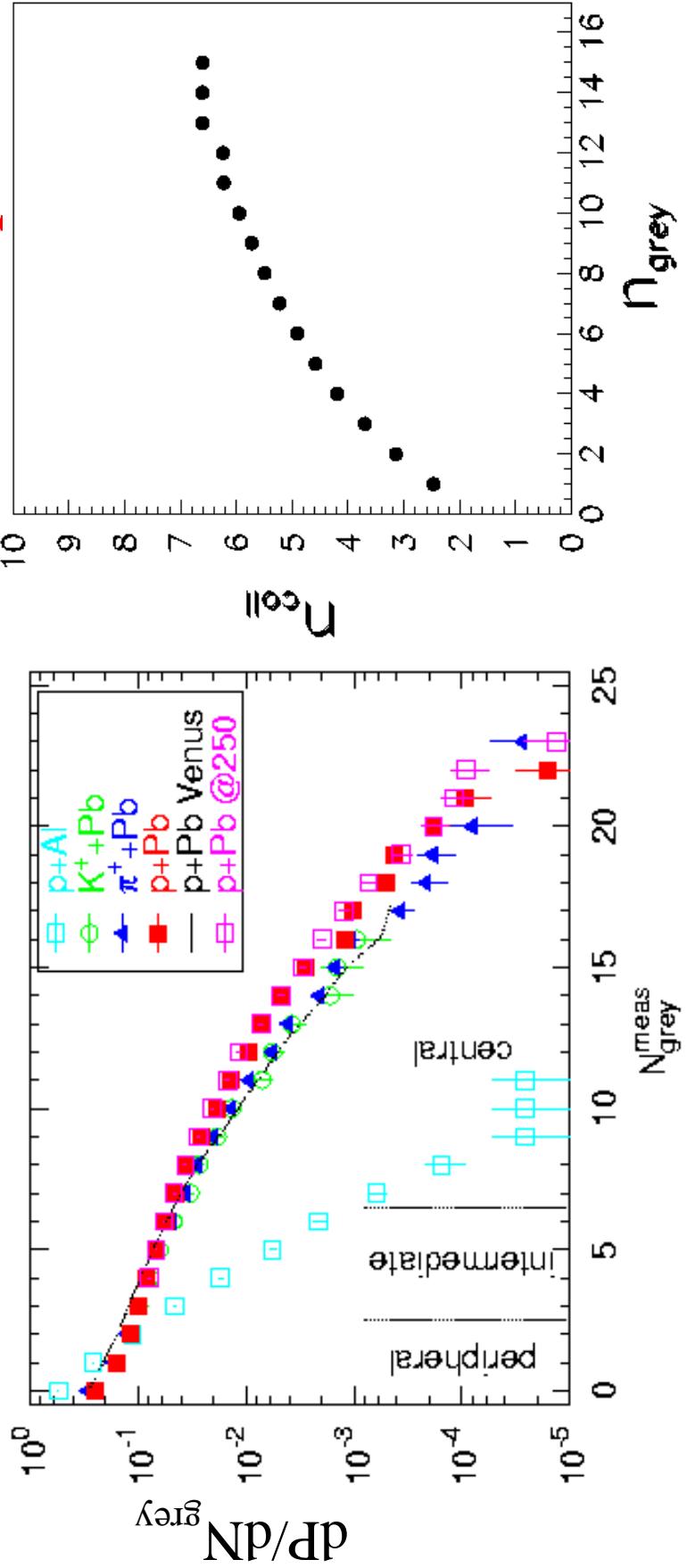
Chemakin *et al*, PRC
60, 024902 (1999)



- Parameterize $N_{\text{grey}}(v)$
- Convolute with Glauber $P(v)$
- Fit to $dN/dN_{\text{grey}} \rightarrow P(v, N_{\text{grey}})$
- Project to get $\langle v(N_{\text{grey}}) \rangle$
- **Beware:** distribution of v may be important.

NA49 $N_{\text{grey}} \Rightarrow \langle v(N_{\text{grey}}) \rangle$

Minimum Bias



- N_{grey} distributions similar to E910

- Obtain $\langle v(N_{\text{grey}}) \rangle$ from VENUS.

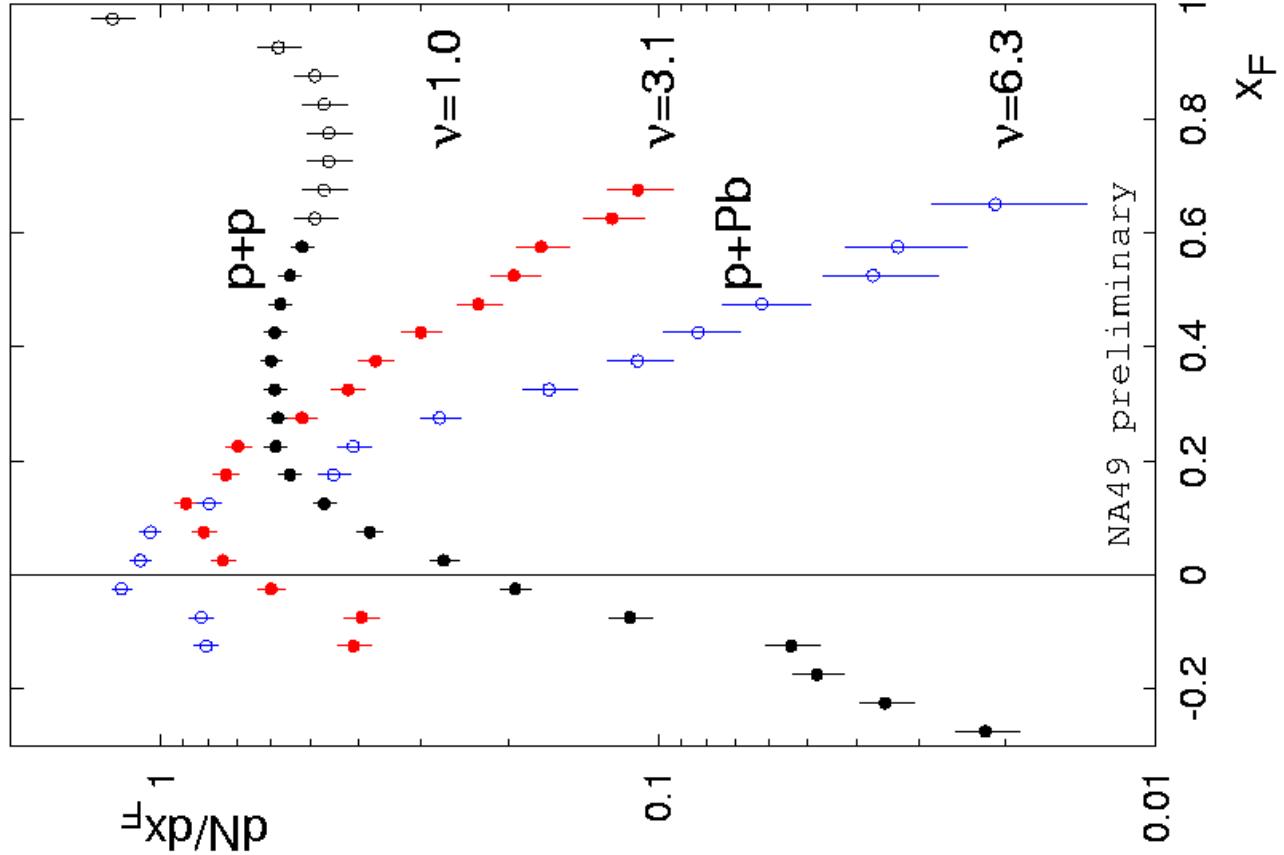
- Note: some data obtained with non-minimum bias N_{grey} distribution

Projectile Stopping/Fragmentation

- Returning to the use of “ X ” for studying stopping/fragmentation.
 - Provides more detail on high-momentum region.
- Which X ?
 - $X_F = p_L^*/|p_L|_{\max}$ ($-1 < X_F < 1$)
 - ⇒ But what is center of mass in p-A ?
 - $X_{\text{lab}} = p_{\text{beam}}/p_{\text{beam}}$ ($0 < X_{\text{lab}} < 1$)
 - ⇒ But where is p-p center of mass ?
 - $X_+ = (E + p_L)/(E + p_L)|_{\text{beam}} \approx X_{\text{lab}}$
- At high momentum X 's are \approx same.
 - ⇒ E.g. at AGS, $X_{\text{lab}} \Rightarrow X_F$ for $X_{\text{lab}} > \sim 0.35$
- Note: $dn/dy \approx X dn/dX$

NA49 : Stopping

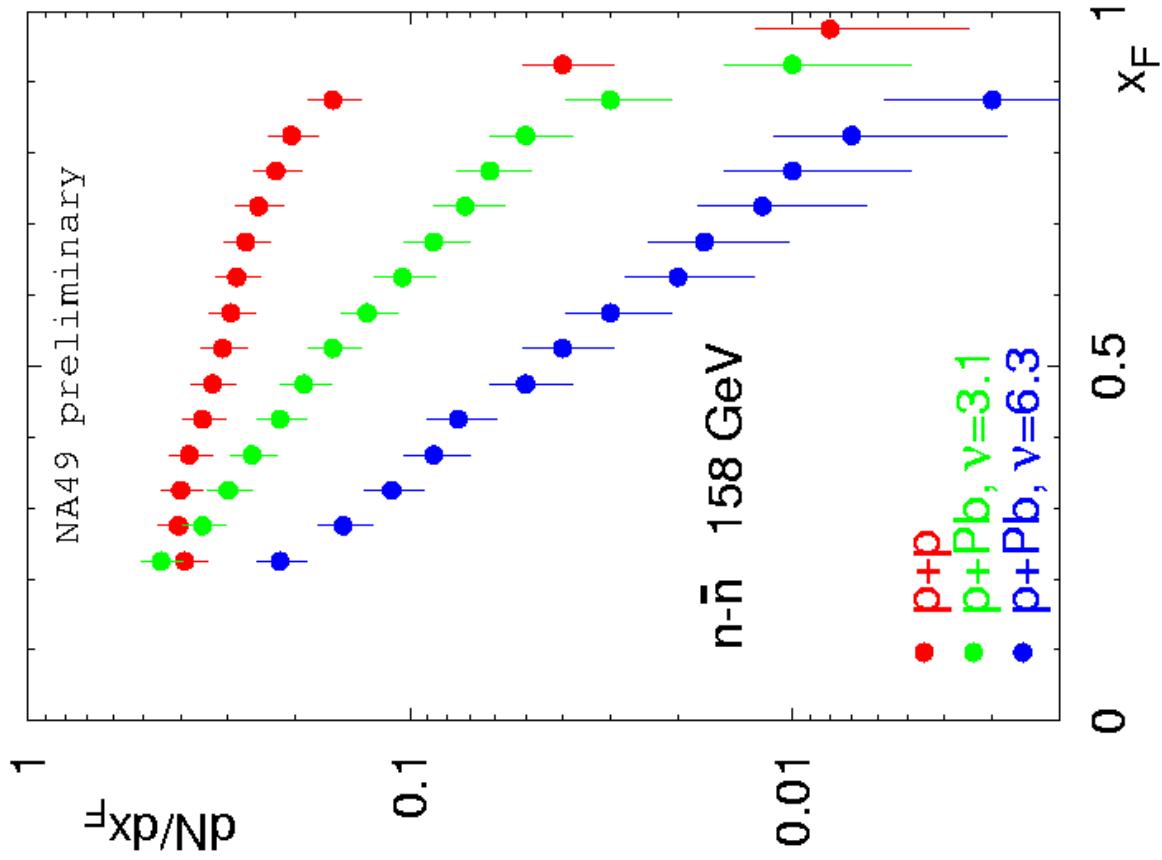
Projectile component of net proton spectrum



- Analysis by **G. Veres**
- Measure, remove boosted target protons with π -Pb.
- Get clean measure of projectile proton spectrum.
 - After ~ 6 collisions, protons stopped to center-of-mass.
 - Symmetric or not ?
 - $\langle \Delta y \rangle \geq 3$ (?)

NA49 - Leading Neutrons

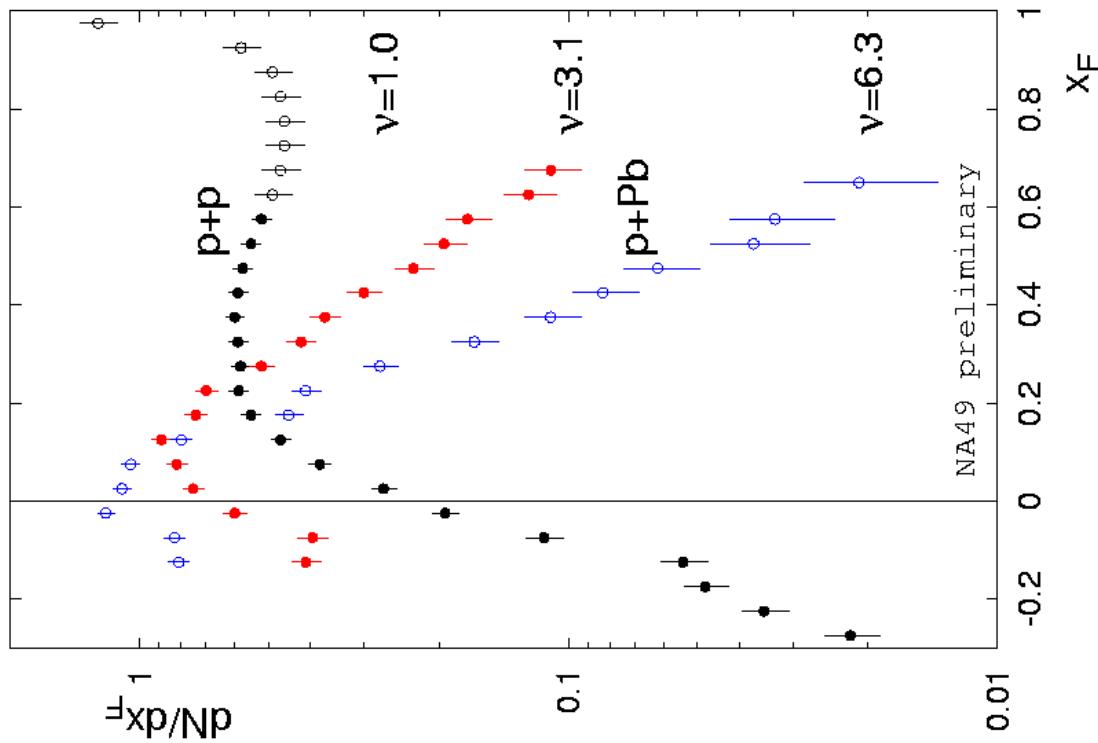
neutron 'stopping'



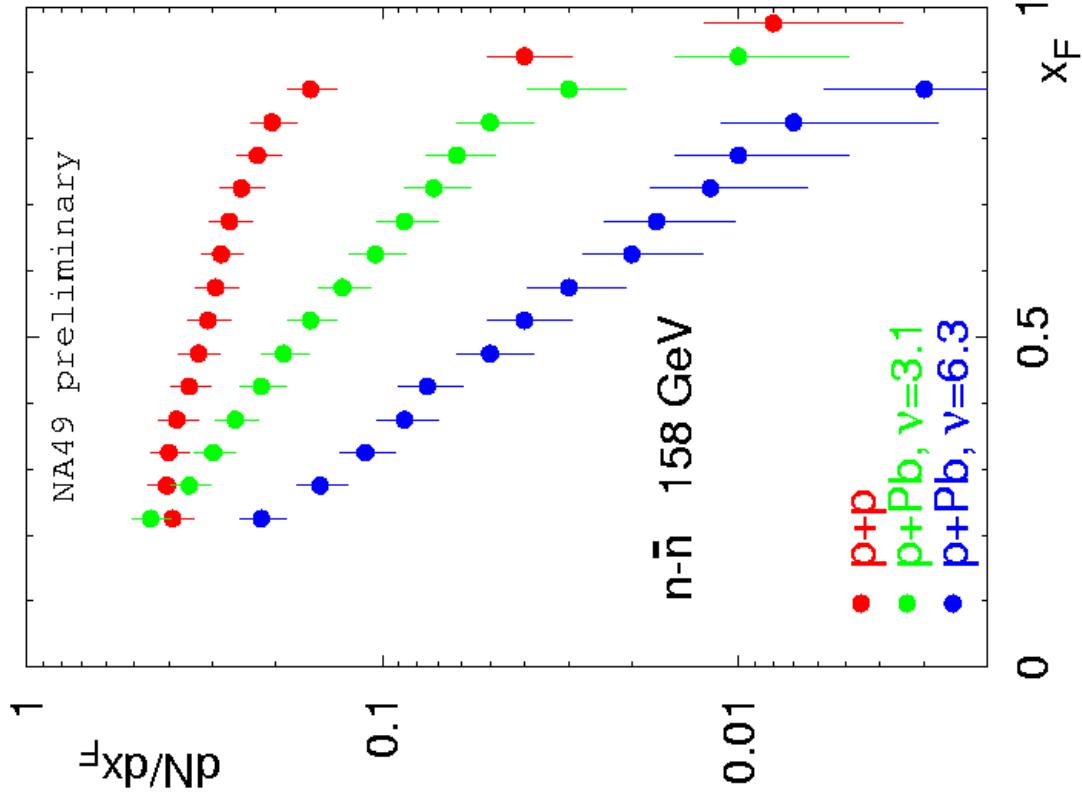
- Usually missing part of stopping :: neutrons
- NA49 measures in hadron calorimeter.
- Measure & subtract anti-neutron.
- **Beautiful result.**

NA49 Proton & Neutron

Projectile component of net proton spectrum



'neutron 'stopping'



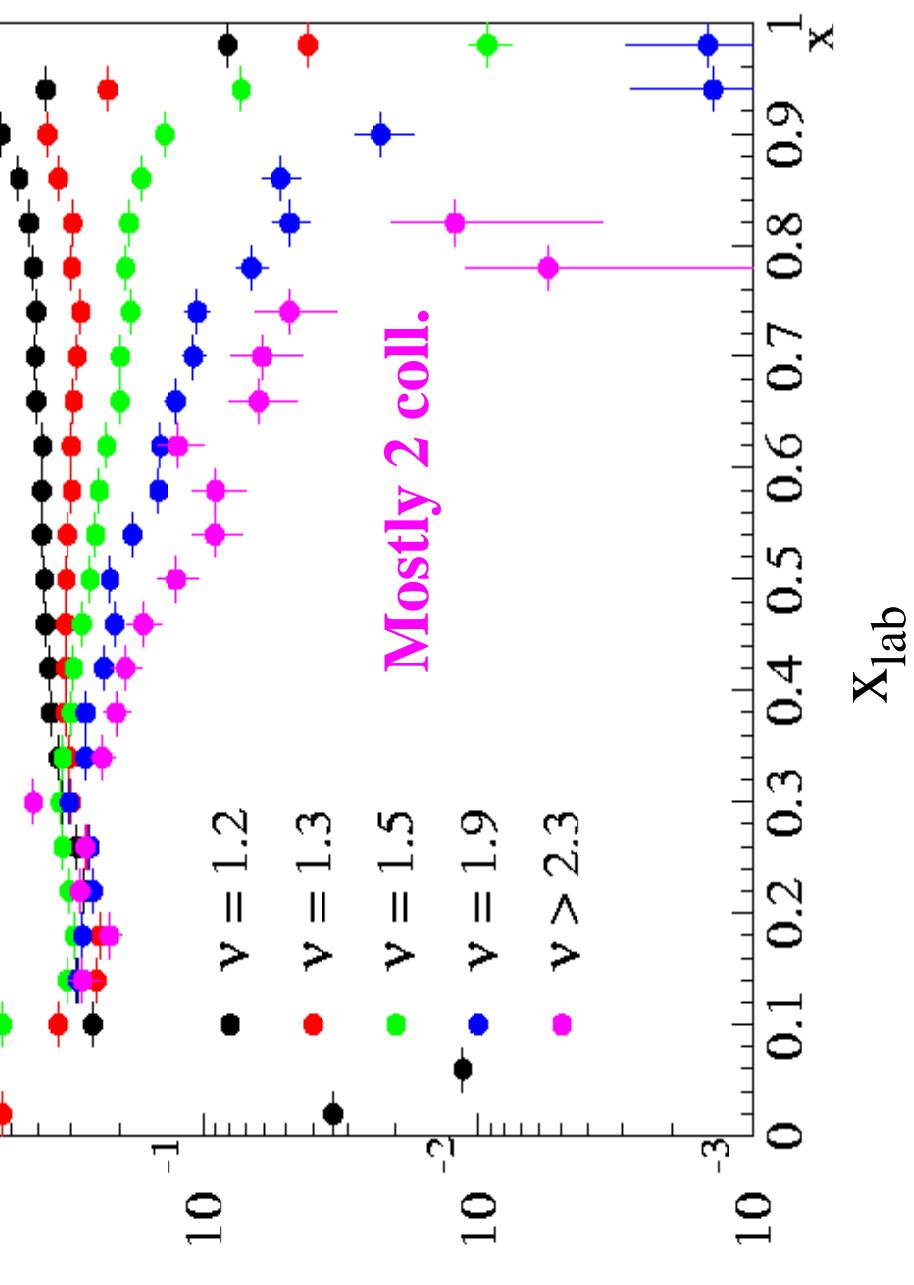
- After 3 collisions, neutron & proton similar.
- See talk by A. Tai from E941 in parallel session.

E910 - Projectile Fragmentation

Proton $\chi dnd\chi$ for pBe 12 gev/c

E910 Preliminary

Mostly 1 coll.



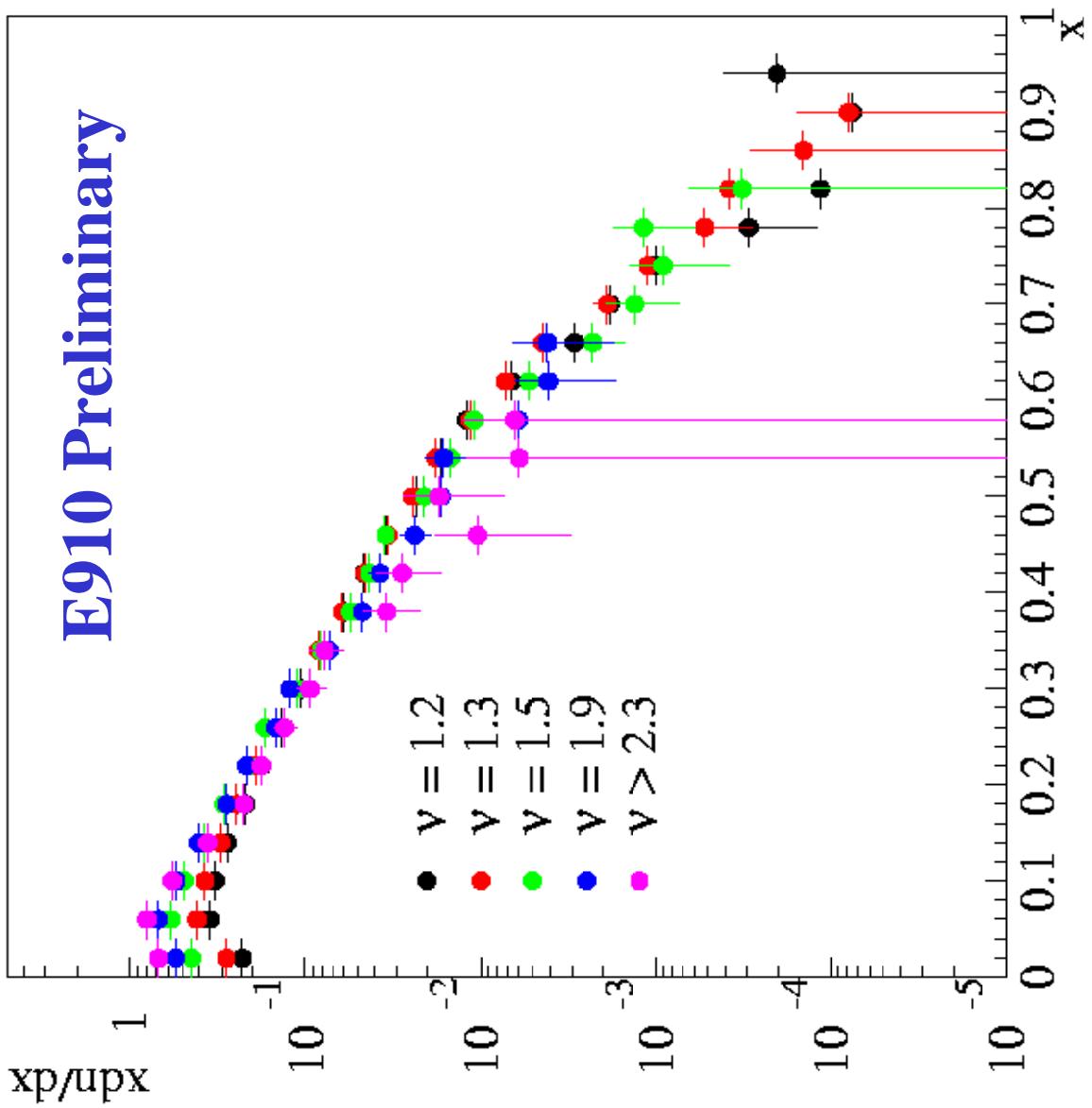
Analysis by
H. Hiejima

Dramatic
change in
proton
spectrum
between 1st, 2nd
collision

E910 – Fragmentation π^-

$\pi^- \times d\text{d}x$ for pBe 12 gev/c

E910 Preliminary



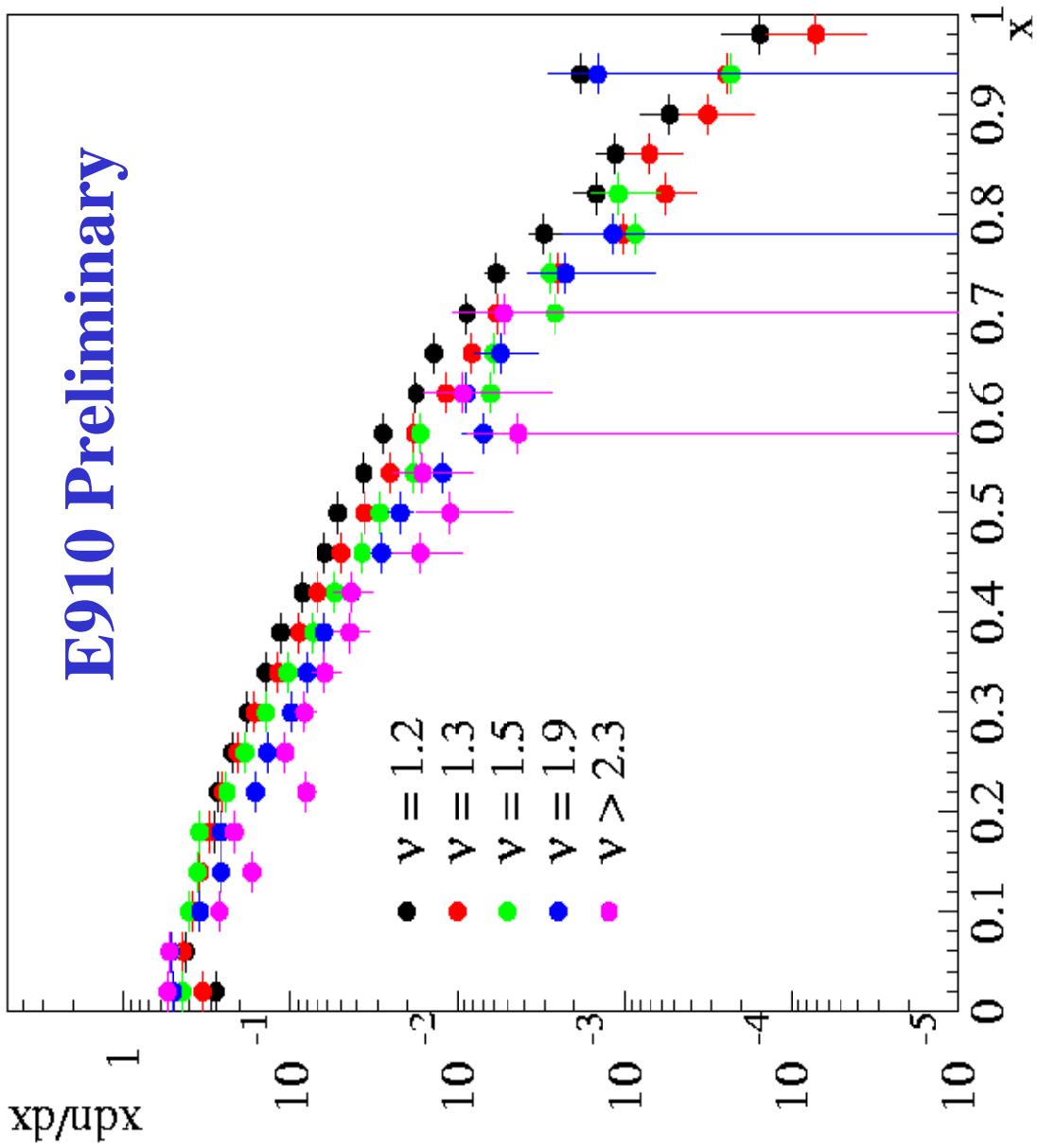
\approx No change in
 π^- spectrum
between 1st, 2nd
collision !!

Stop the baryon
but not the
energy ??

E910 Fragmentation π^+

$\pi^+ \times dndx$ for pBe 12 gev/c

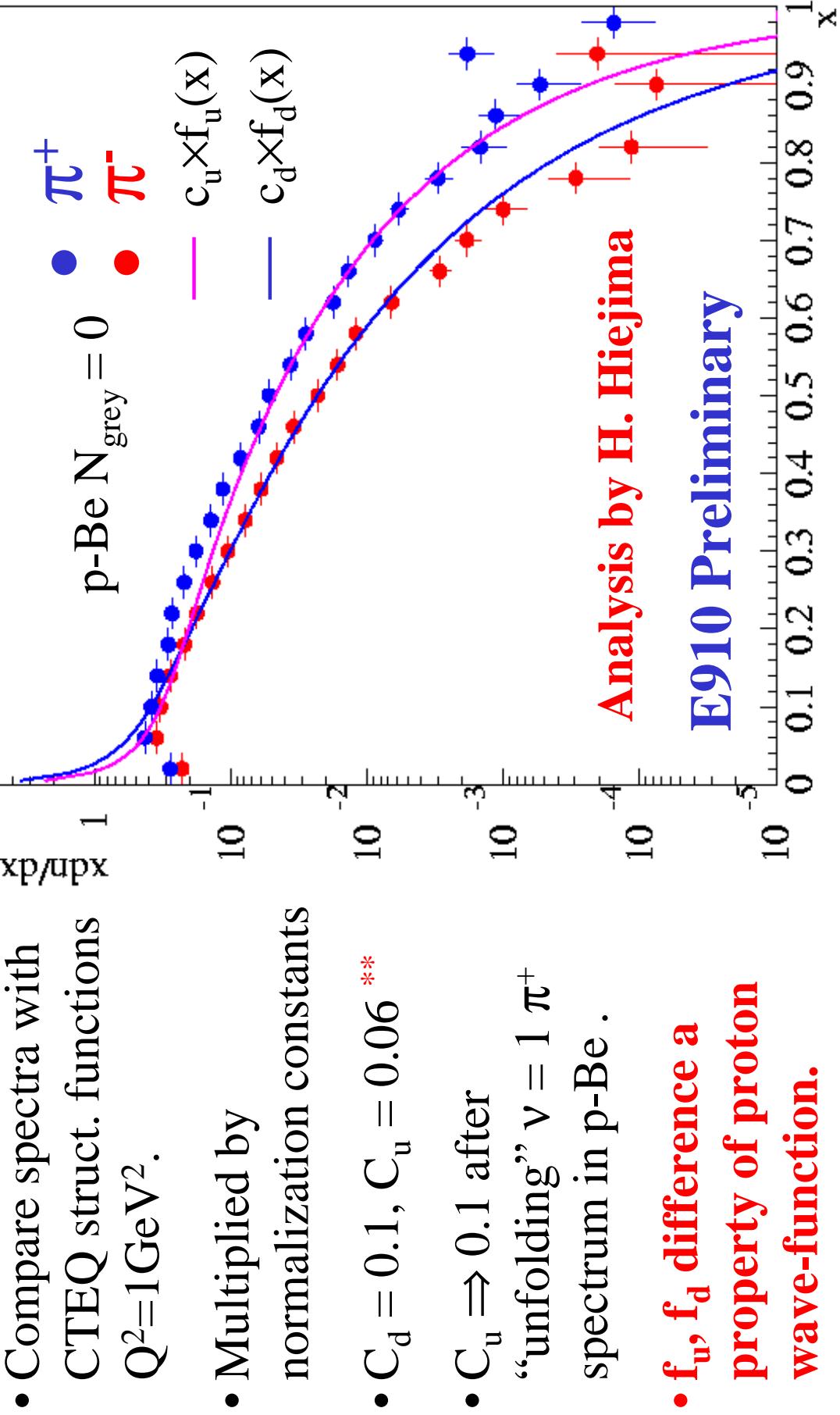
E910 Preliminary



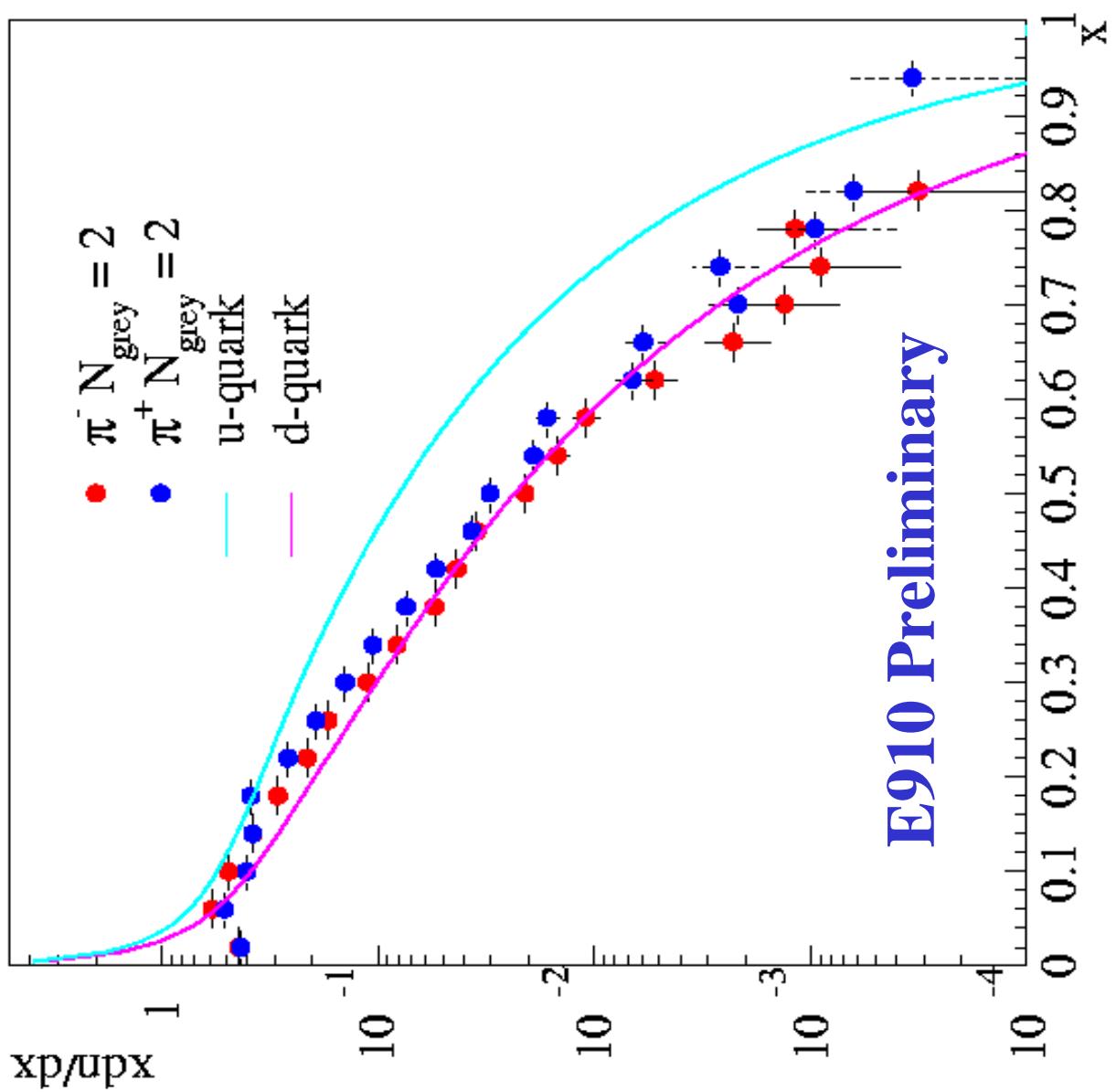
Clear decrease
in π^+ spectrum
between 1st,
2nd collision !!

E910 – Fragmentation π^* 's

- Where do large- x pions come from ?
- One explanation: “spectator” valence quarks
 - Momentum spectrum reflects quark momenta.



E910 – Fragmentation π^* 's



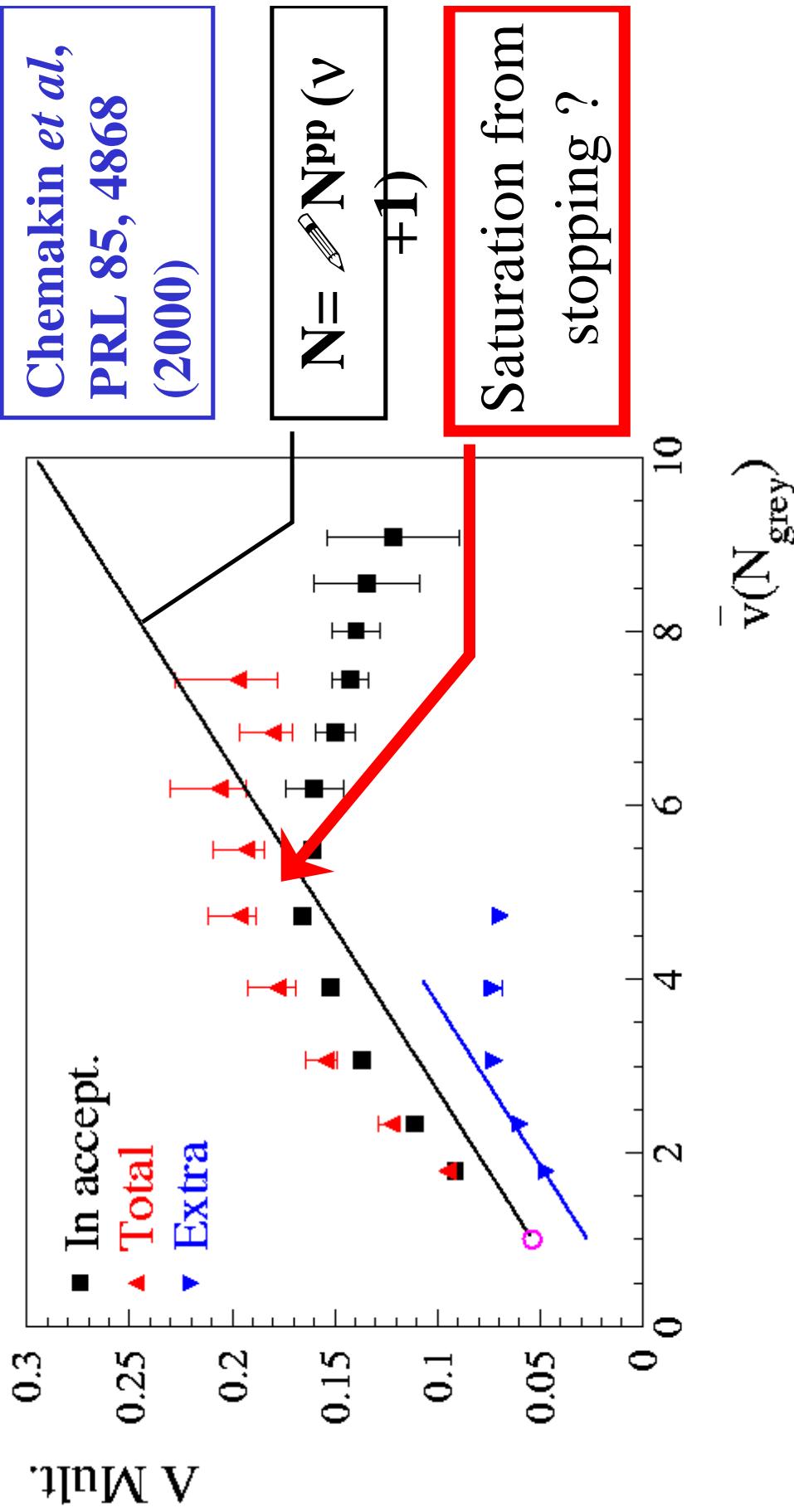
After 1 collision,
u quark excess
& f_u / f_d shape
difference are
gone !!

Proton
dramatically
altered in first
(few) collision(s)

Strangeness in p-A

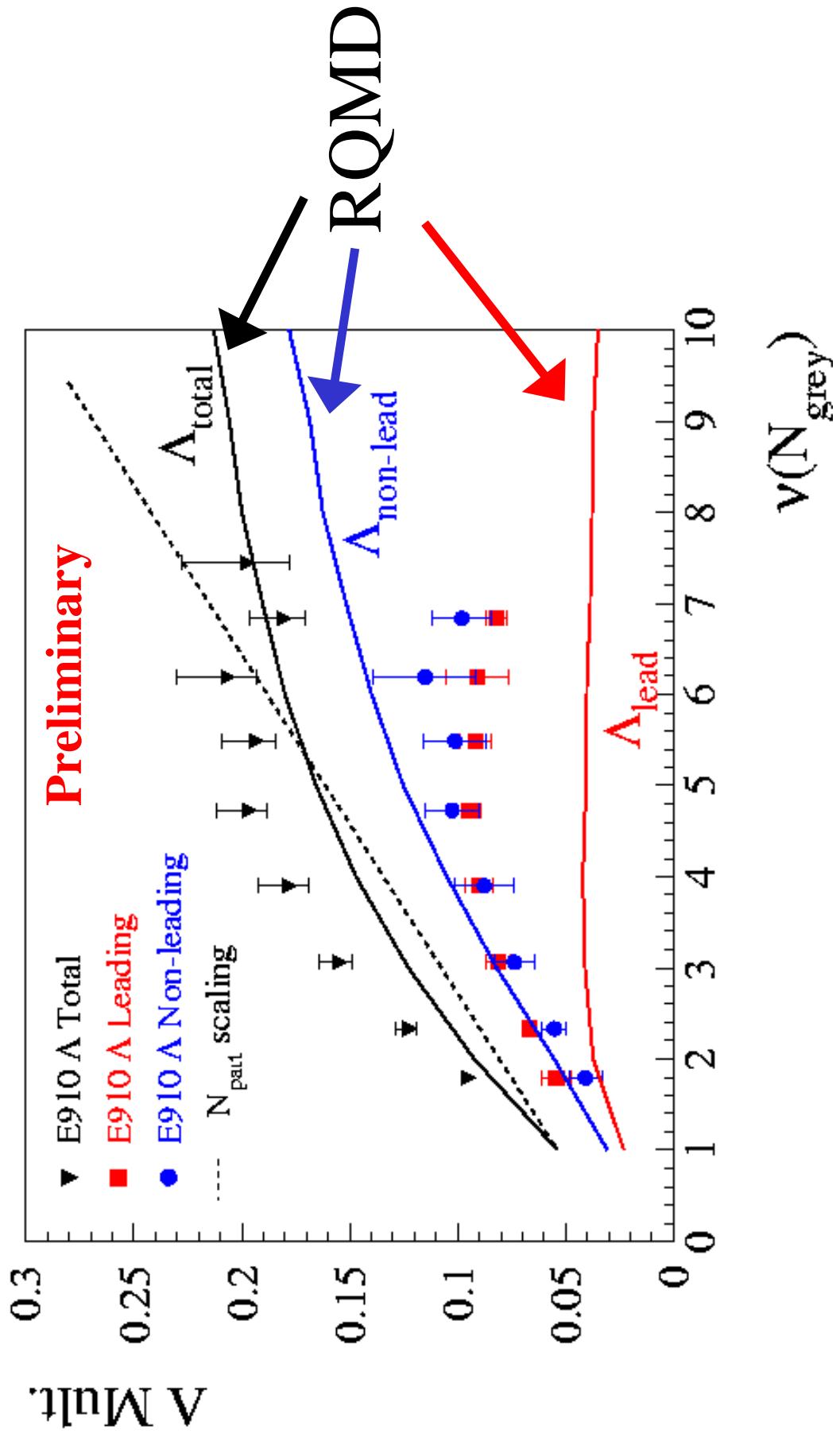
- Conclusions from past data
 - Strangeness **is** enhanced at AGS (**E802**)
 - Strangeness **is not** enhanced @ SPS (**many**)
 - ⇒ **Caveat:** No experiments measured strangeness with N_{grey} selection with good statistics.
- Prejudices:
 - Enhancement at AGS due to **rescattering**
 - ⇒ Associated production of YK pairs
 - Enhancement could result @ SPS in events with color-rope formation.
- **Not from “ordinary” p-A dynamics**
- But Capella: di-quark breaking, strange sea, ...

E910: 17.5 GeV p+Au, Λ Yield vs v



- Excess Λ production observed over # participant scaling of p-p
- $\Rightarrow N_{\Lambda}^{\text{proj}} = v \times \cancel{N}_{\Lambda}^{pp}$ for $v \leq 3$???

E910, 17.5 GeV/c p+Au, Leading Λ



- Ask “are Λ ’s leading baryon” event by event
 ⇒ Excess due to leading Λ ’s (**from projectile**)
- ⇒ Not reproduced by RQMD.

p-Be dN/dy distribution

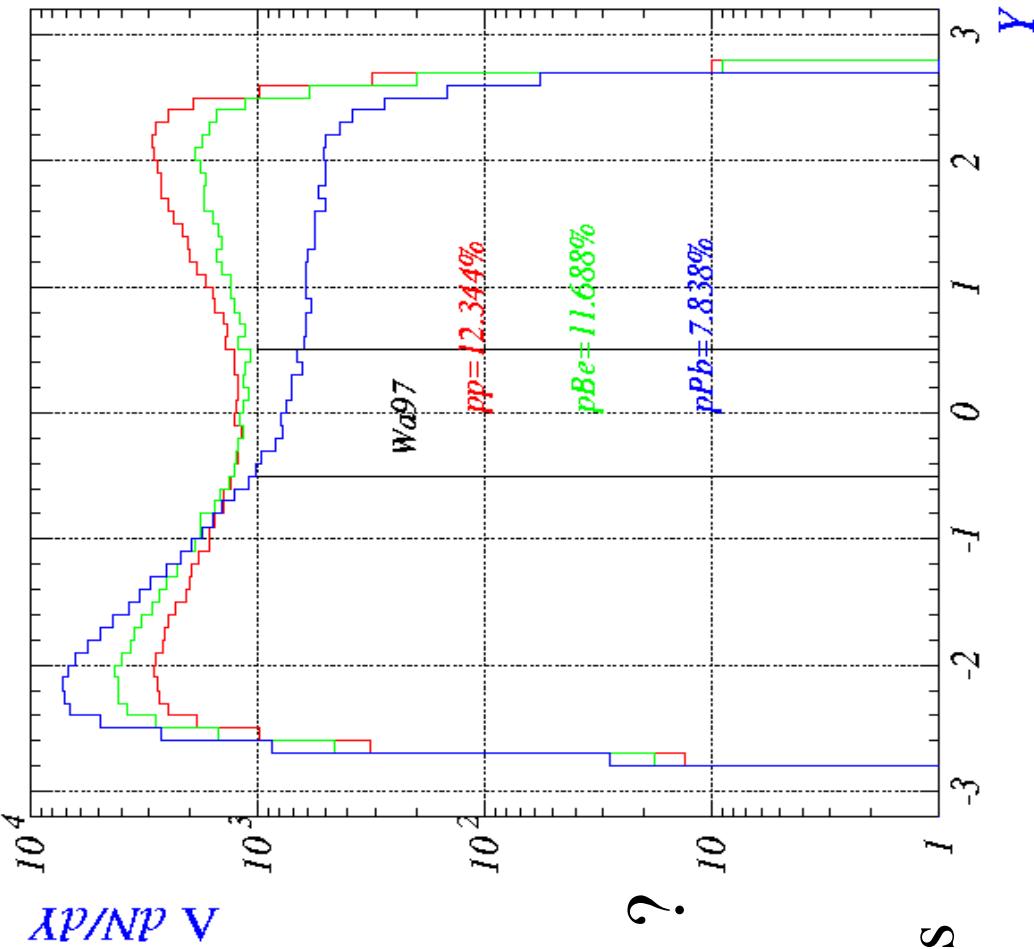
- **Study by R. Soltz**

- Parameterization of p-Be & p-Pb data by Geist, Kachelhofer
(ZPC 71:45 (1996))

- p-Be dn/dy peaked at ends like p-p

- Pb-Pb peaked in middle?
 - Get (large) artificial enhancement.

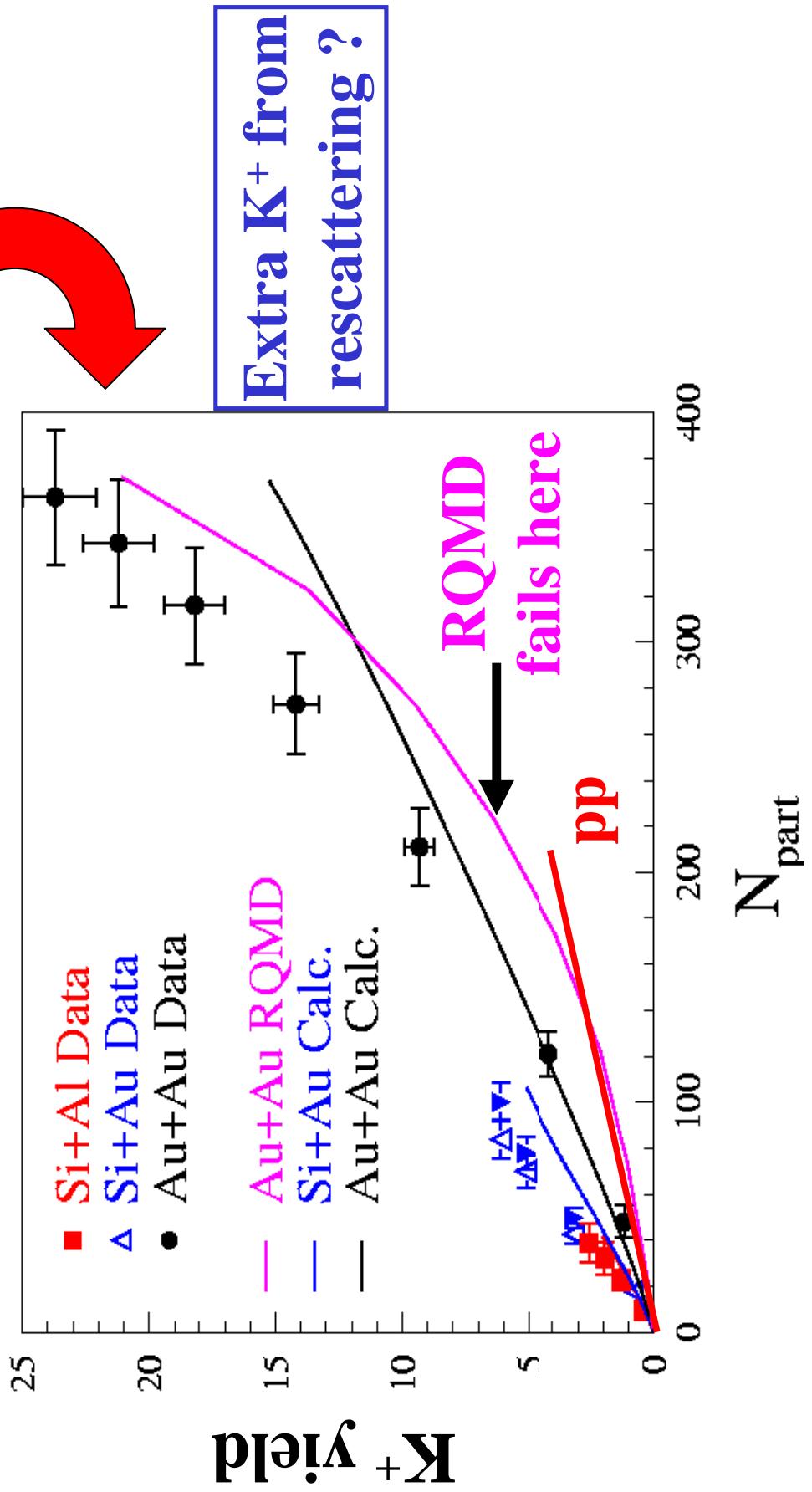
– $\sim \times 1.7$ assuming Pb-Pb is Gaussian with $\sigma = 2$.



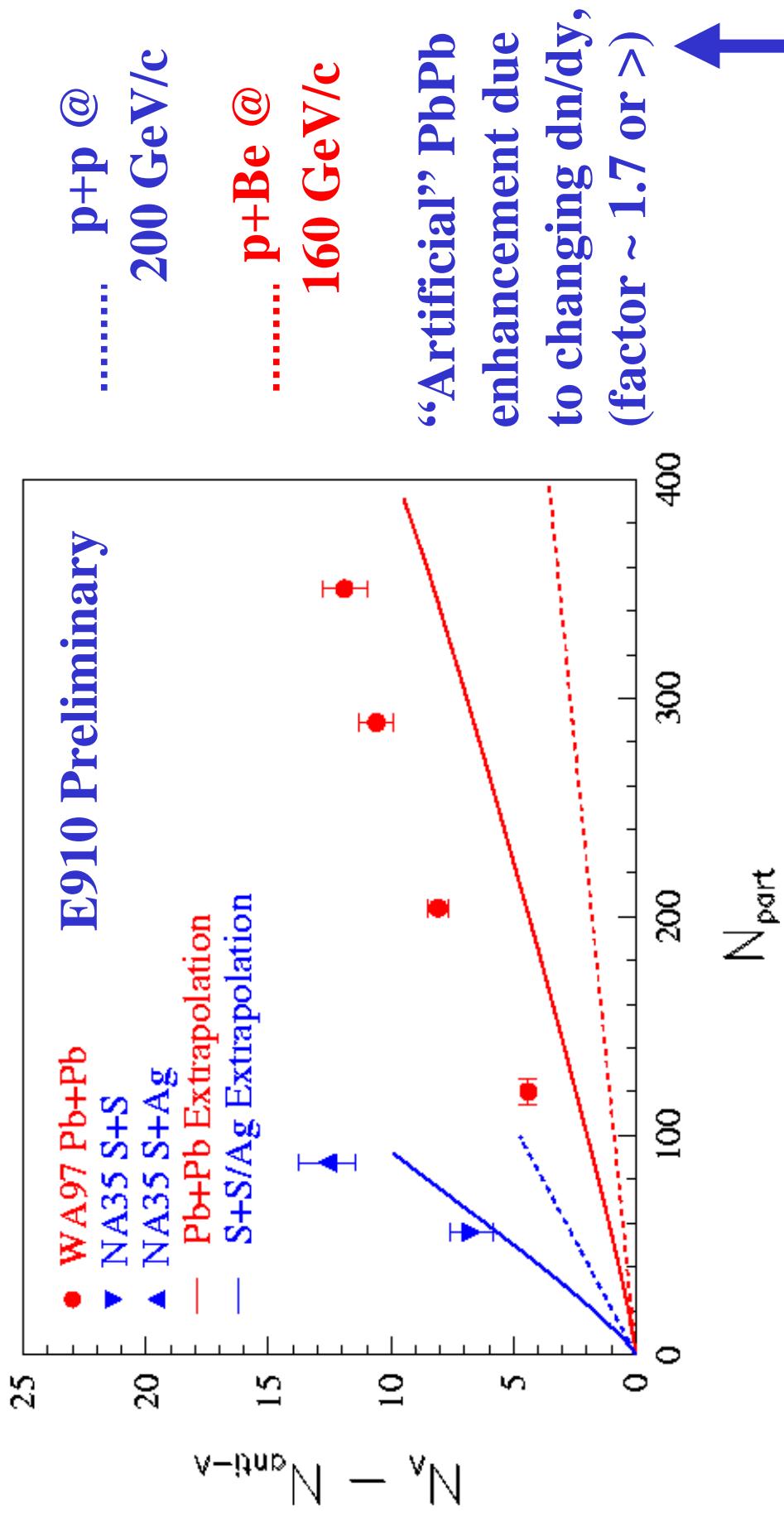
We need the full dn/dy distribution.

E910, Extrapolate to Si+A, Au+Au K⁺

- Glauber Si+A, Au+Au calculation by BAC, Yang:
 - Apply, $N_{\text{part}}^{\Lambda} = N_{\text{pp}}^{\Lambda} \times V, V \leq 3$.
 - Compare to E859, E866 data (assume K⁺ $\propto \Lambda$).
 - Account for > 75% of K⁺ yield except



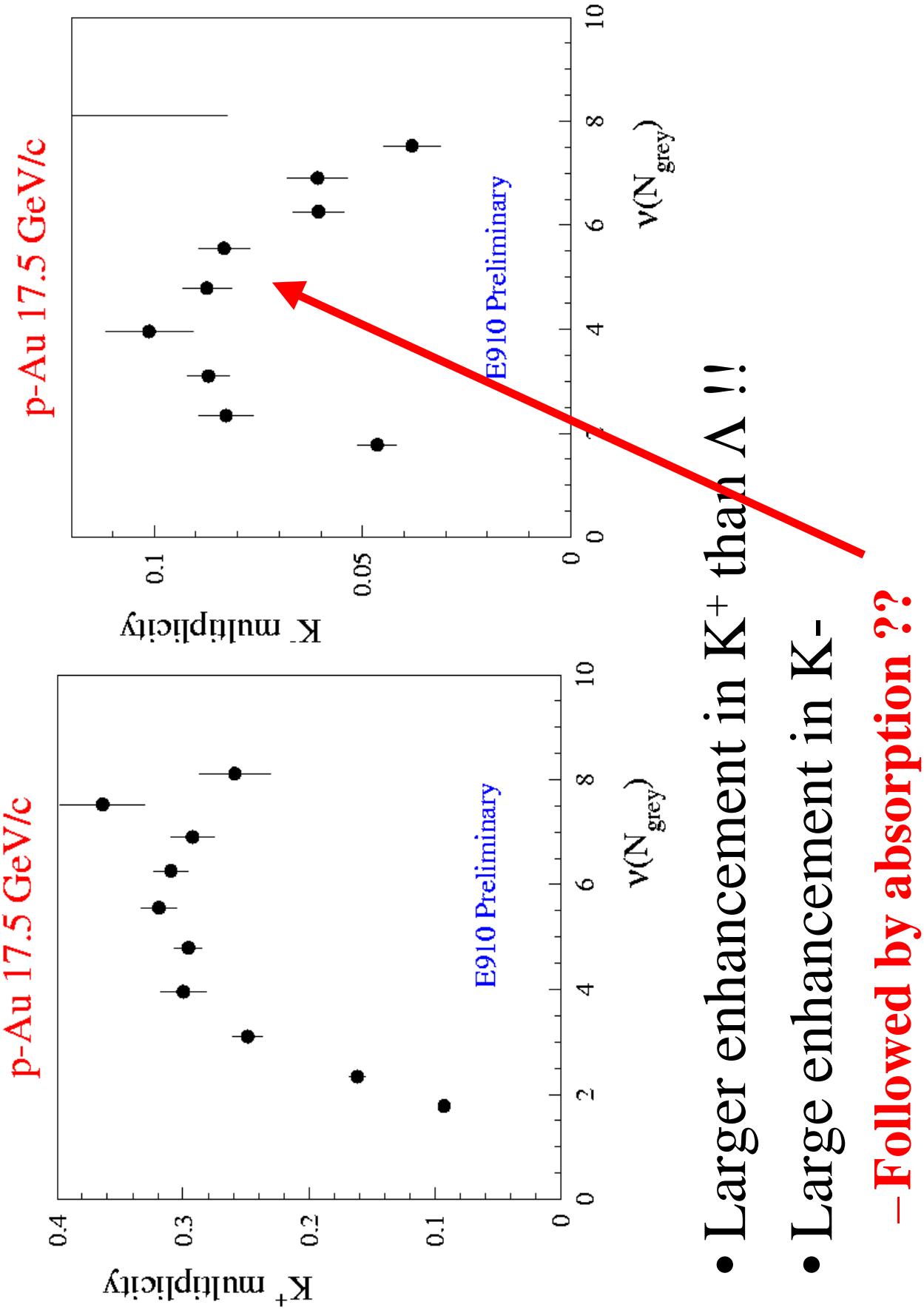
E910 Extrapolation to SPS ??



- All energy dependence in extrapolation is in N_{pp} .
 - Apply to SPS energies using N_{pp} , N^{Be} .
- **Can reproduce S+S, S+Ag enhancement.**
- **Not all of Pb+Pb (but ...)** —

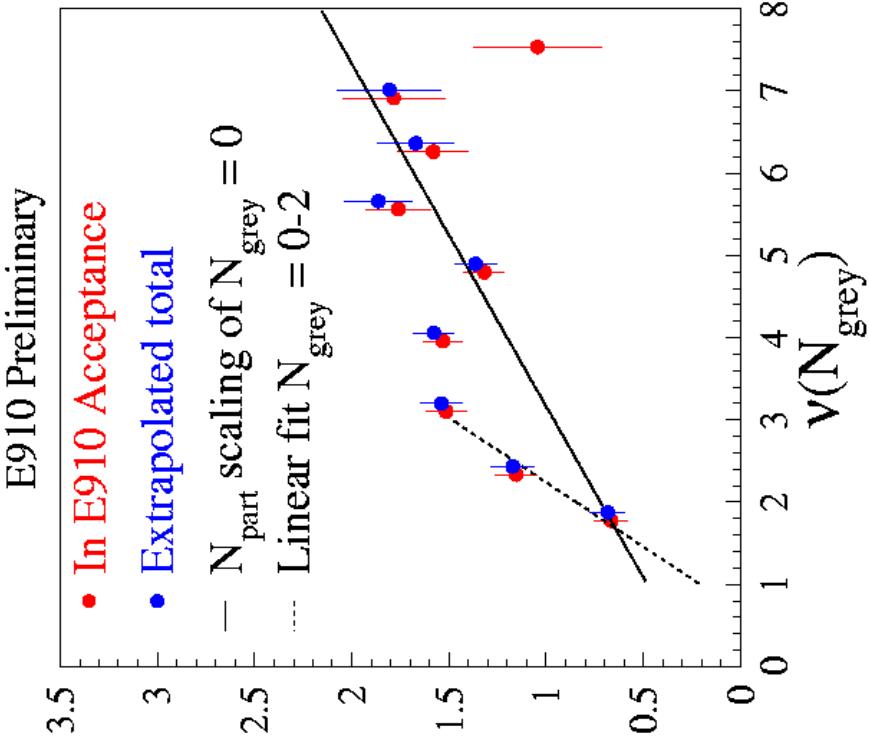
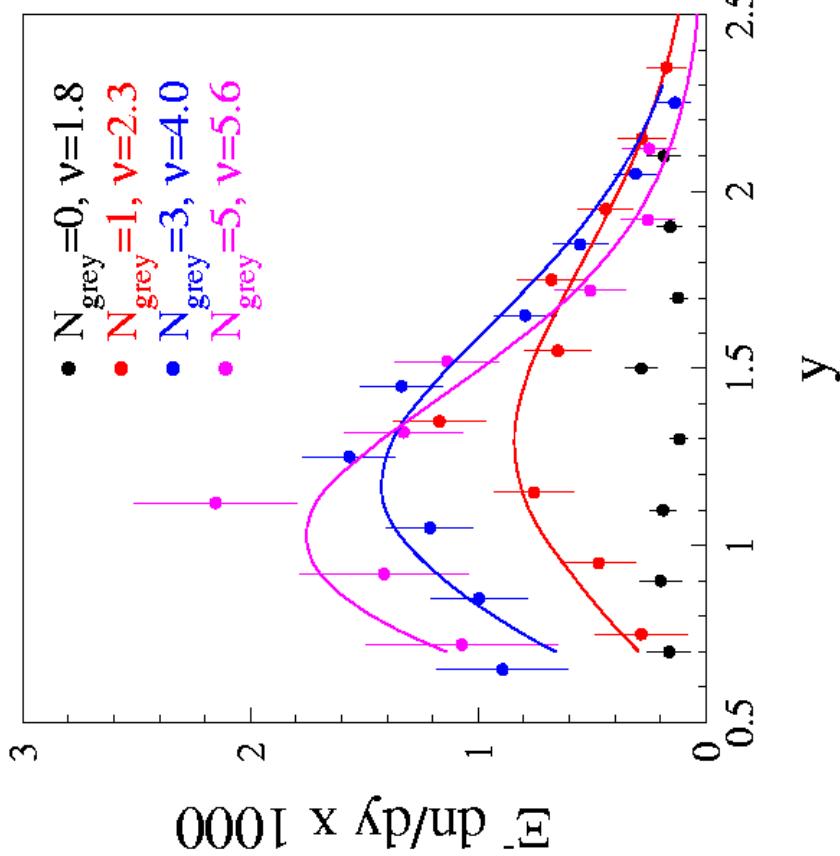
E910 New Result :: Charged Kaons

- Reconstructed via $K \Rightarrow u, K \Rightarrow \pi\pi$ (A. Frawley).



- Larger enhancement in K^+ than Λ !!
- Large enhancement in K^-
 - Followed by absorption ??

E910-17.5 GeV/c p-Au Ξ -Production



- Rapid increase in Ξ yield with y .

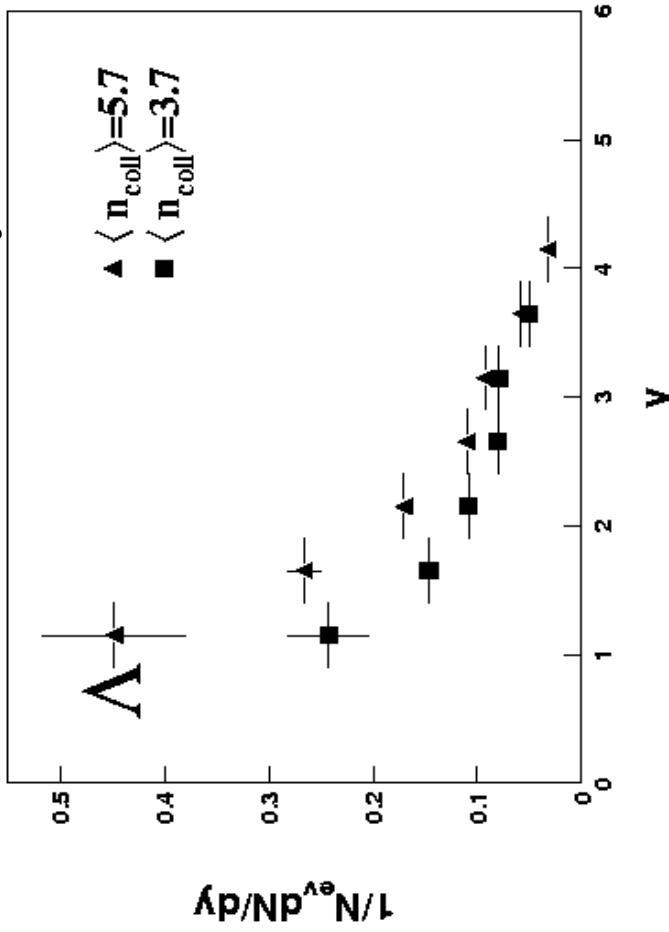
\Rightarrow **Inconsistent with # participant scaling**

- $> \times 4$ increase in Ξ yield over $v = 1$ with any reasonable extrapolation $\Rightarrow > \times 8$ in $A+A$
- Also due to projectile ?! (starts above y_{NN})**

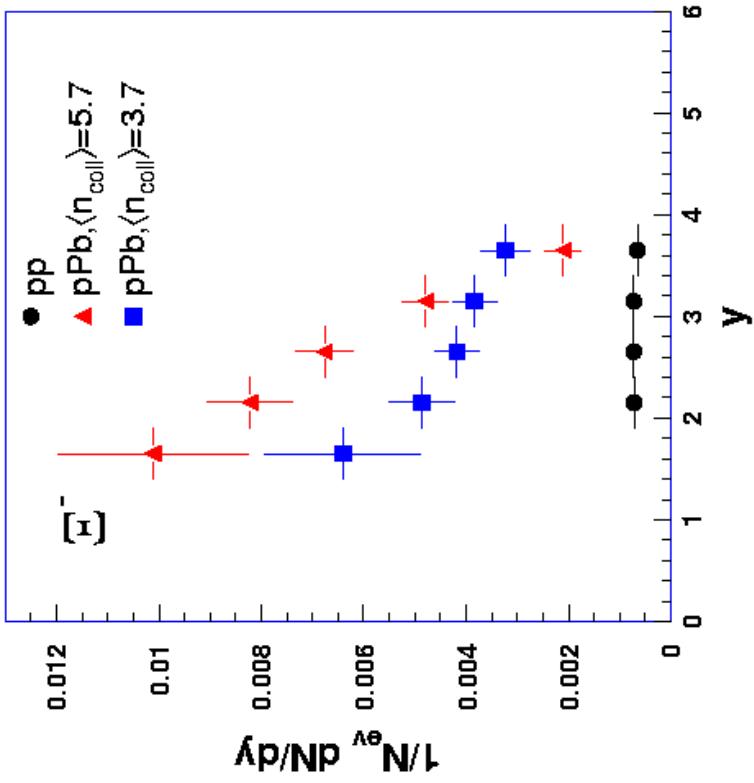
NA49 p-Pb Strange Baryons

Analysis by T. Susa

NA49 Preliminary



NA49 Preliminary



- Two bins in N_{grey} : **0-6** ($\langle \nu \rangle = 3.7$), **>6** ($\langle \nu \rangle = 3.7$)

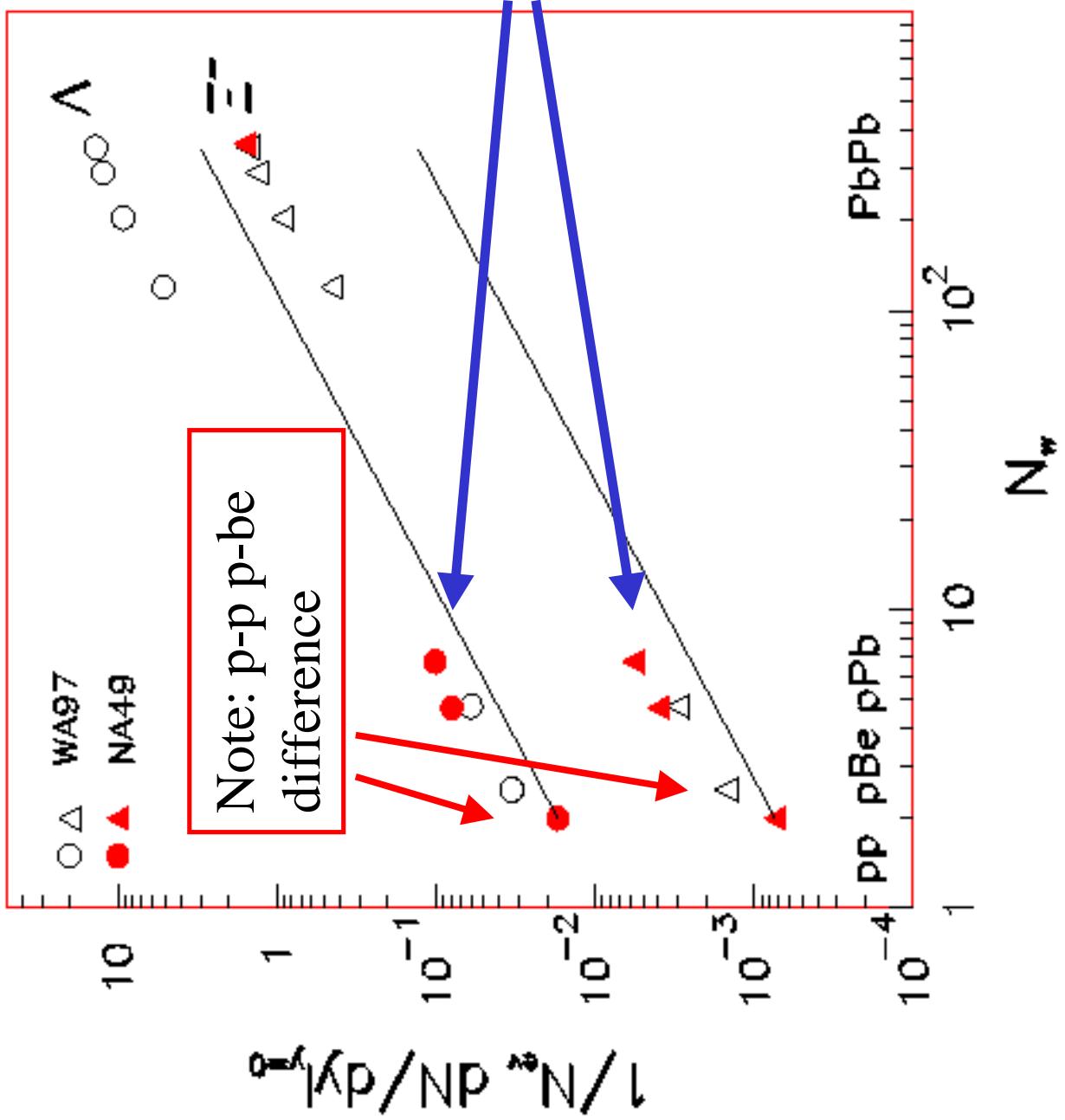
• Slow growth in Λ dn/dy .

• Fast growth in Ξ^- dn/dy

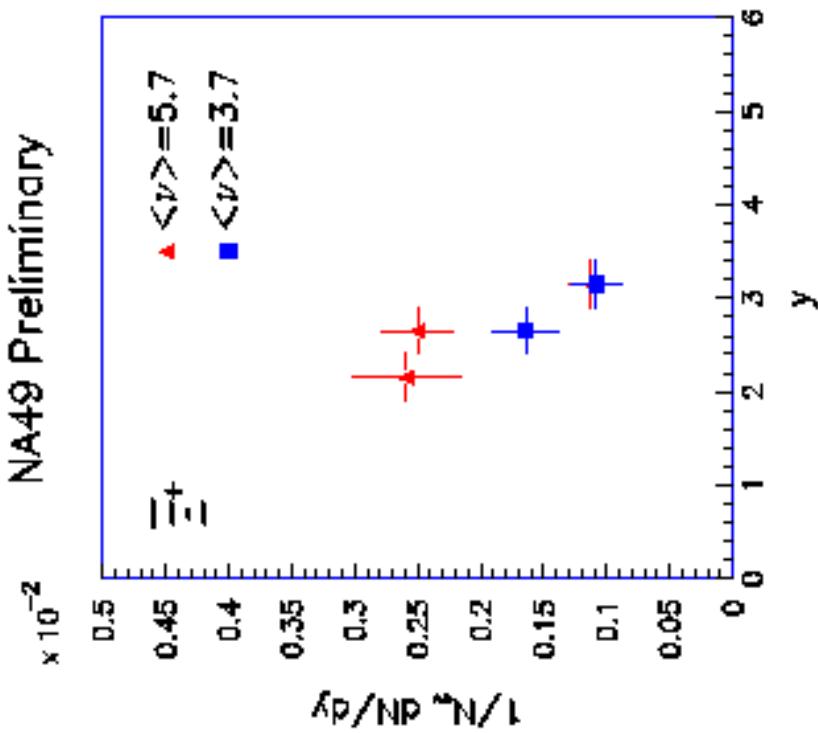
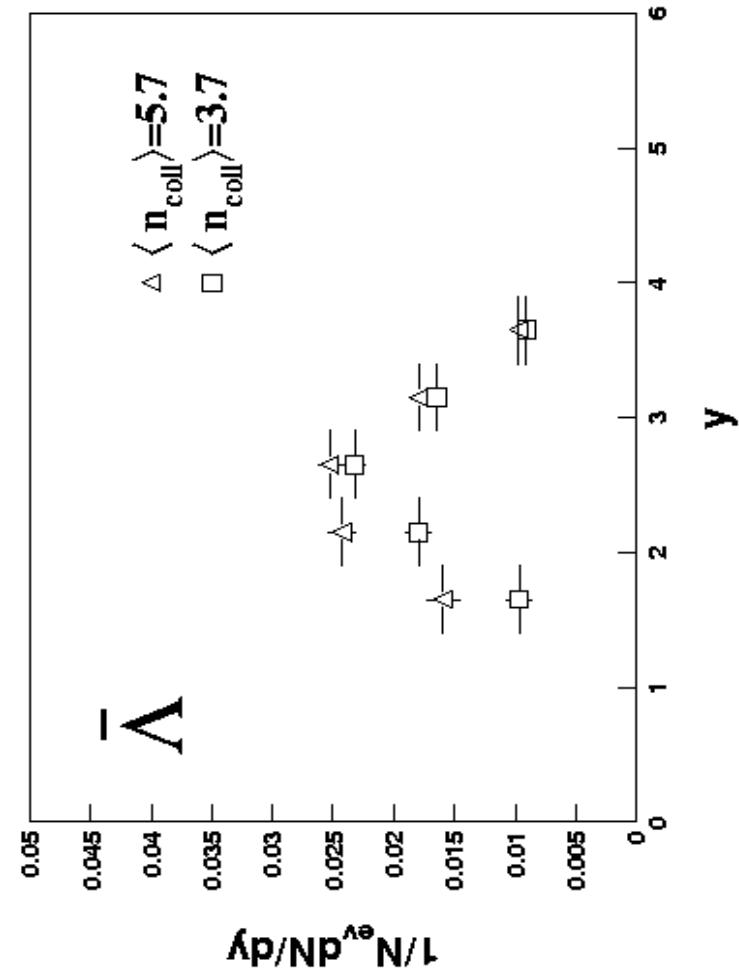
– Initially even forward of y_{NN}

NA49 Wounded-Nucleon Analysis

NA49 Preliminary



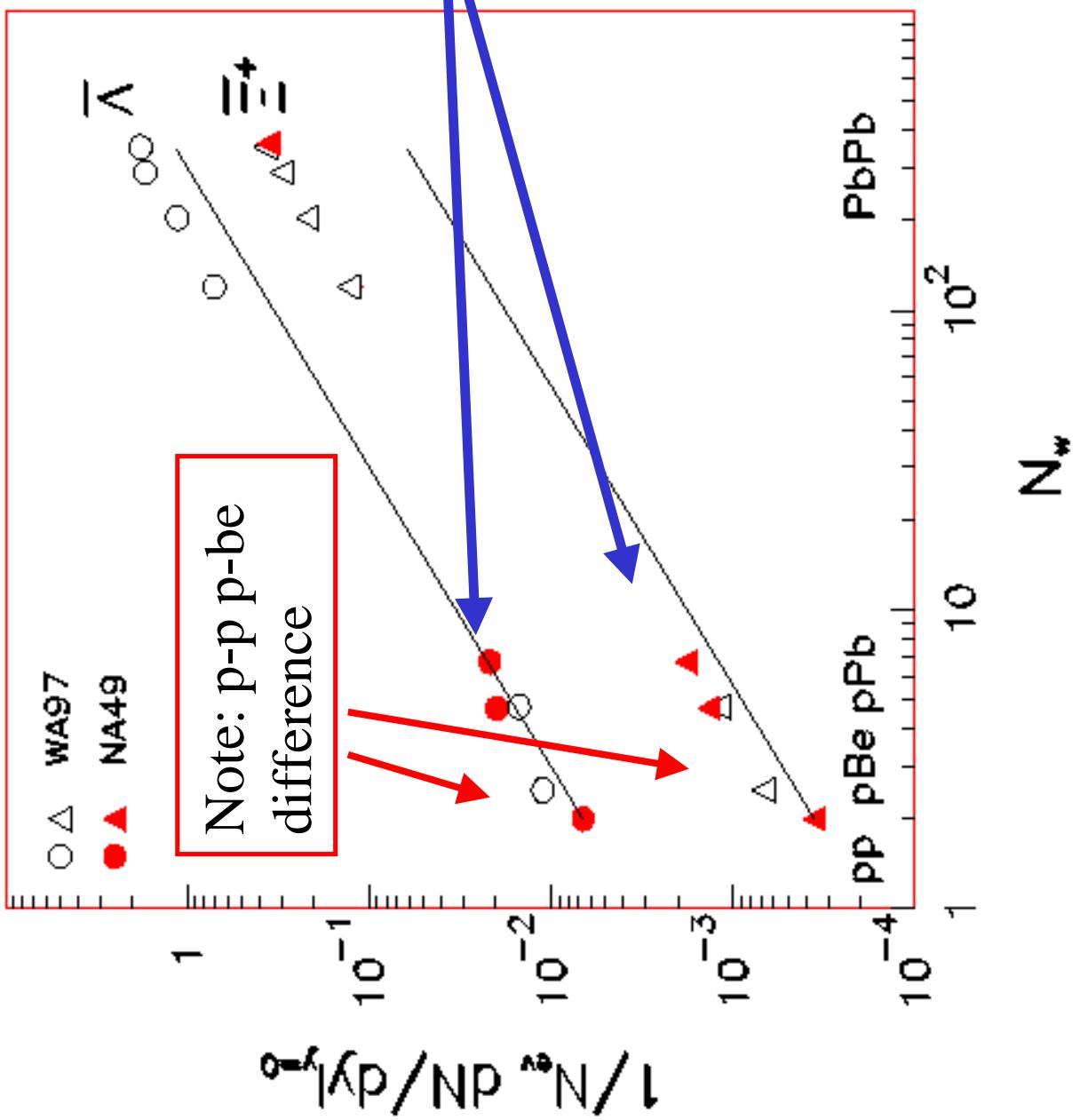
NA49 Strange anti-baryons



- Anti-baryon distributions peaking below y_{NN}
 - **More strongly for anti-E than anti-Lambda.**
 - Is this an effect of “stopping”?
 - What about effects of annihilation?

Wounded-Nucleon Analysis (reprise)

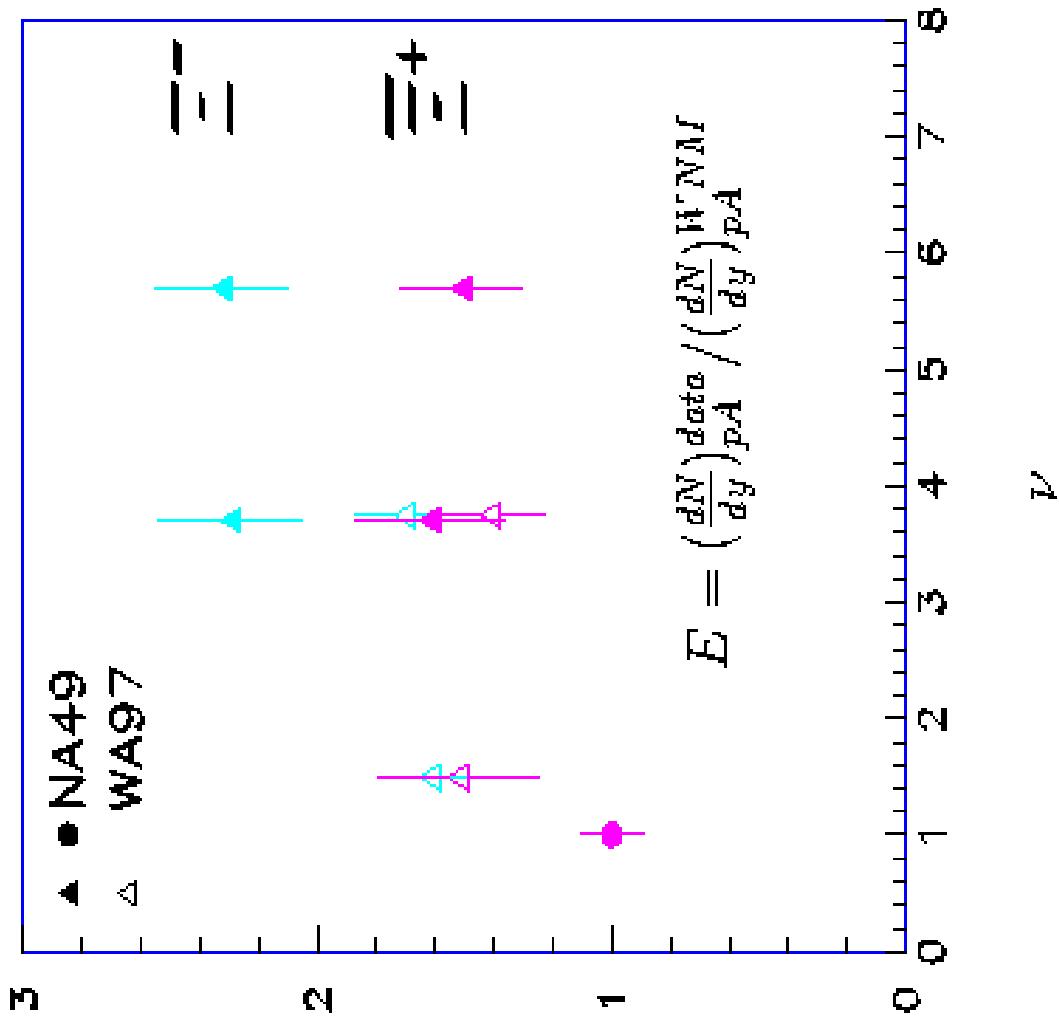
NA49 Preliminary



Smaller
enhancements
for anti-
baryons

Enhancements, WN Interpretation

NA49 Preliminary



$$E = \left(\frac{dN}{dy}\right)_{pA}^{\text{data}} / \left(\frac{dN}{dy}\right)_{pA}^{\text{WNNM}}$$

Significant but modest enhancements over wounded-nucleon expectation

$$\bullet \left(\frac{dN}{dy}\right)_{pA} = E\left[\left(\frac{1}{2}\nu + \frac{1}{2}\right)\left(\frac{dN}{dy}\right)_{pp}\right]$$

Enhancements, Alternative

- Suppose take alternative interpretation:
 - Enhancement solely due to projectile
 - Do similar calculation to E910
 - Can approximately reproduce Pb+Pb
 Λ, Ξ , yields.

Strangeness -- Synopsis

- Clear signs of strangeness enhancement in p-A at both AGS and SPS.
 - **Already in p-Be collisions @ SPS ?!**
- Clear association in E910 between excess Λ production & projectile fragmentation.
- Enhancement present in multi-strange baryons
 - ⇒ **Not just associated production ?!**
- Suggestion in NA49 that excess strangeness also associated with projectile.
- Non-trivial behavior of anti-baryons (role of junction ??)
 - Shift backward with more collisions.
 - ⇒ **Following the projectile proton ?**
- **Increase in anti-lambda yield after 1st collision @ AGS ?!**
 - ⇒ **See talk in Session III by S. Mioduszewski**

Conclusions

- We are probing the interaction of a proton in a nucleus with unprecedented precision.
- Extensive evidence for non-trivial behavior in first few interactions of proton.
 - Rapid stopping.
 - Changes in π^+ x distribution, **loss of memory ??**
 - Strange baryon, kaon, anti-baryon production.
- Due to break-up of proton ?
 - Dynamics destroy hadrons in initial state ??
- **We must understand this physics and feed back into cascade models to properly test for new physics in A-A.**

Relevance to RHIC

- Exciting possibility to use centrality dependence in p-A to study hard processes in nuclei – **never been done before.**
 - K_T , jet dE/dx in cold nucleus, evolution of color-octet states, shadowing,
- Fly in the ointment:
 - Contributions from higher-order diagrams in topological exp. will produce “extra” multiplicity.
 - E.g. junction has 25% extra associated multiplicity.
 - **If multiple interaction of proton leads to these higher-order contributions, then will get soft multiplicity that grows faster than N_{part} .**
- Need to study in mini-jet free environment
 - Still an important role for fixed-target p-A.